

## **Toxicity of lithium ion battery chemicals -overview with focus on recycling**

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## Preface

This report contains an overview of toxicity risks with lithium ion batteries. It was performed in the context of the Swedish Scope-LIB project financed by Energimyndigheten, Dnr 2019-002597. It has been carried out by Mats Zackrisson and Steffen Schellenberger at RISE IVF. A list of acronyms and abbreviations used is provided below.

Ah	Ampere hours
BM	Black mass
CAS	Chemical Abstract Services
CO <sub>2</sub> eq	Carbon dioxide equivalents
DC, DEC	Diethyl Carbonate
CF <sub>4</sub>	Perfluorinated methane
DMC	Dimethyl carbonate
EC	Ethylene Carbonate
ECHA	European Chemicals Agency
FEP	Fluorinated ethylene propylene
EMC	Ethylmethyl carbonate
HF	Hydrofluoric acid
LCO	Lithium Cobalt Oxide
LFP	Lithium iron phosphate, LiFePO <sub>4</sub> , battery cell
LIB	Lithium ion battery
LiPF <sub>6</sub>	Lithium hexafluorophosphate
LMB	Lithium metal batteries
LMO	Lithium Manganese Oxide
NCA	Lithium nickel cobalt aluminium oxide
NMC	Lithium nickel manganese cobalt oxide battery cell
PBT	Persistent Bioaccumulative and Toxic substances
PFAAs	Perfluoroalkyl acids
PFAS	Perfluorinated alkylated substances
PFOA	Perfluorooctanoic acid
PFHxA	Perfluorohexanoic acid
POF <sub>3</sub>	Phosphoryl fluoride
POPs	persistent organic pollutants
PVDF	Polyvinylidene fluoride
VC	Vinyl Carbonate
Wh	Watt hours

## Contents

<b>Preface</b>	<b>3</b>
<b>Figures</b>	<b>4</b>
<b>Summary</b>	<b>5</b>
<b>Chemical content of today's lithium ion cells</b>	<b>6</b>
<b>Production and use phase</b>	<b>9</b>
<b>End-of-life phase</b>	<b>14</b>
LiPF <sub>6</sub> forms hydrogen fluoride and phosphoryl fluoride	17
Thermal pre-treatment	18
Summary and recommendations for the end-of-life phase	19
<b>Future outlook</b>	<b>20</b>
<b>References</b>	<b>20</b>

## Figures

Figure 1. The most common lithium chemistries 2015, 2016 och 20259..	7
Figure 2. Production of LIB cells, adapted from <sup>13</sup>	10
Figure 3 Main construction types of LIB cells: a) wound cylindrical, b) button cell, c) wound prismatic and d) pouch cell <sup>14</sup>	11
Figure 4. Lithium ion traction battery pack	12
Figure 5. Diagnostic and disassembly phase	15
Figure 6. Pre-treatment phase	16
Figure 7. Decoking of black mass as envisioned in the ReLion project <sup>19</sup>	16
Figure 8. Smelting and lithium separation as envisioned in the ReLion project <sup>19</sup>	17
Figure 9. Four ways of thermal conditioning <sup>25</sup>	19

## Tables

Table 1. Electrolyte and PVDF content in NMC333 <sup>1</sup>	7
Table 2. Electrolyte chemicals and binders in LIB cells-unreacted	8
Table 3 Electrolyte chemicals and binders in LIB cells - potential reactions.....	13

## **Summary**

In the end-of-life phase the risks related to toxicity, fire and high voltage inherent in the traction LIB life cycle become apparent and amplified. LIBs are a green technology but contain different hazardous substances, that can be emitted especially during fire events. These emissions are of high risks since chemical transformation processes are not well understood so far.

Additional risk occurs during production of raw materials such as highly fluorinated organic chemicals used in LIBs e.g. for binder materials. Due to the electrochemical stability of fluorinated materials their use might be unavoidable to produce batteries with a long life. However, their production, use and disposal need to be controlled. A high temperature treatment in recycling is a possibility to control emissions in the end-of-life phase.

Any laboratory, recycling facility or actor involved in the end-of-life phase of LIBs must carry out risk assessment for their unique activities and equipment and develop and maintain site specific safety protocols for their personal.

*Many of the ingredients in modern lithium ion battery, LIB, chemistries are toxic, irritant, volatile and flammable. In addition, traction LIB packs operate at high voltage. This creates safety problems all along the life cycle of the LIB. This is a short overview of the health and safety risks during the life cycle of LIBs with a special focus on the end-of-life phase. It is recommended that any actor involved in the end-of-life phase of LIBs carry out risk assessment for their unique activities and equipment and develop and maintain site specific safety protocols for their personal.*

## **Chemical content of today's lithium ion cells**

Nickel manganese cobalt oxide, **NMC**, chemistry will be the dominating battery chemistry for the coming decade, see production figures for 2015 and 2016 and prognosis for 2025 in Figure 1 below. An NMC333-cell will therefore be used as an example of chemical content of LIB cells. The other LIB chemistries, Lithium Iron Phosphate, LFP, Lithium Cobalt Oxide, LCO, Lithium Nickel Cobalt Aluminium Oxide, NCA and Lithium Manganese Oxide, LMO have very similar electrolyte and binder content, see for example bill of materials for NMC, LFP and NCA<sup>1</sup> and for LMO<sup>2</sup>.

Many safety concerns with today's LIB chemistries are focused on the liquid electrolyte<sup>3</sup>. A very common LIB electrolyte is a 1-molar solution of Lithium **hexafluorophosphate (LiPF<sub>6</sub>)** in 1:1 Ethylene Carbonate: Diethyl Carbonate and 2% Vinylene carbonate. Other Lithium conductive salts including compounds with highly fluorinated counter ions might be used in the production of LIB electrolytes as well. An overview of new Li- salts for LIBs is shown in a review by Bushkova et al<sup>4</sup>.

The amount of electrolyte needed is based on the volume of pores in the separator and in the cathode and can often reach 20% of battery cell mass or 10% of traction battery mass<sup>1</sup>. Several chemicals used in LIBs are of high concern (see table 2). An example is **Vinylene carbonate**, an additive with high human and aquatic toxicity<sup>5</sup>. Another common LIB electrolyte ingredient is the flammable solvent Diethyl carbonate (DMC) which is likely to be an acute health hazard since it is suspected to be cancerogenic and toxic to reproduction according to European Chemicals Agency (ECHA)<sup>6</sup>. DMC is often used in a mixture with Ethyl methyl carbonate (EMC).

In addition, **fluoropolymers** such as Polyvinylidene fluoride (PVDF) or **Fluorinated ethylene propylene (FEP)** are used as binder materials for both the negative (anode) and positive (cathode) in nearly all commercial LIBs<sup>7</sup>. **Fluoropolymers as well as highly fluorinated chemicals used in the electrolytes are a potential hazard when it comes to the emissions of persistent organic pollutants (POPs)**<sup>8</sup> related to LIBs. However, the potential risk of fluorinated chemicals associated with LIBs is so far not well understood. This report provides further insights into the chemicals uses in LIBs and their potential risk considering different life cycle phases.

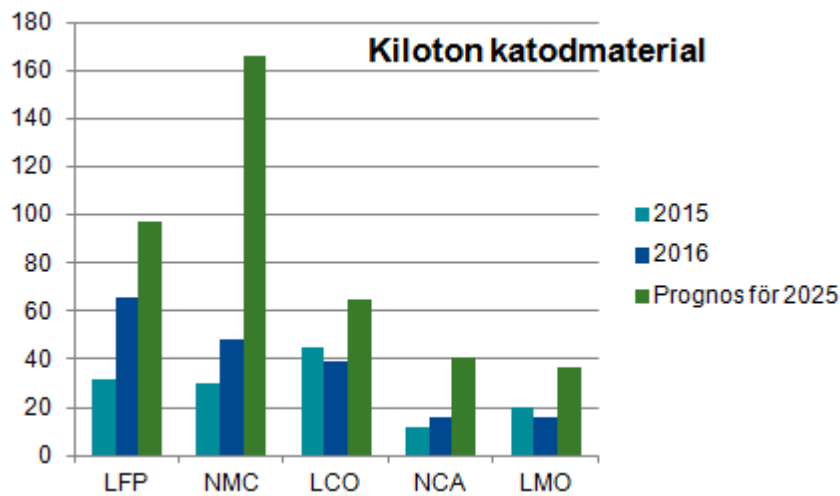


Figure 1. The most common lithium chemistries 2015, 2016 och 2025. Since it is approximately 10 years between production and recycling, what was produced 2015 will be available for recycling 2025.

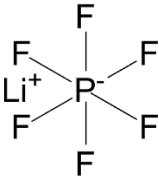
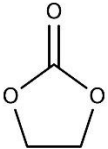
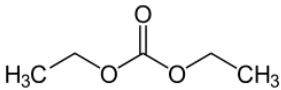
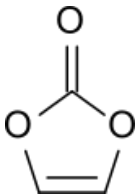
A typical NMC333-cell consist of 16% electrolyte distributed according to Table 1 below. An NMC333 consist of equal amounts of nickel, manganese and cobalt. The NMC333 cell in Table 1 is a 33 Ah cell weighing 800 grams. This is a cell size associated with traction batteries even though smaller cells are also common<sup>1</sup>. Smaller cells would of course contain less electrolyte per cell but similar amounts per ton of cells.

Table 1. Electrolyte and PVDF content in NMC333<sup>1</sup>

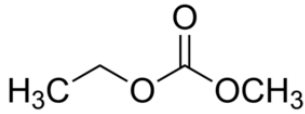
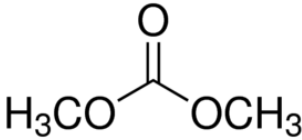
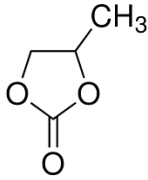
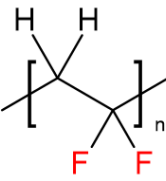
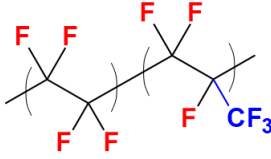
Material	% of electrolyte	% of cell	Gram per NMC333 cell from AESC weighing 800 g	Kg per ton NMC333 cells
Lithiumhexafluorophosphate	11	1,8	14	18
Ethylene carbonate	48	7,7	60	77
Diethyl carbonate	39	6,2	49	62
Vinylene carbonate	2	0,3	2,5	3
Polyvinylidene fluoride (PVDF)	NA	1,4	11,3	14

In Table 2, other commonly used chemicals for LIBs are included as well as hazard statement of the raw materials in the unreacted state.

Table 2. Electrolyte chemicals and binders in LIB cells-unreacted

Material/CAS	Chemical formula	Hazard	Comment
Lithiumhexafluorophosphate CAS 21324-40-3		<b>H302</b> Acute toxicity, oral <b>H314</b> Causes severe skin burns and eye damage <b>372</b> Causes damage to organs through prolonged or repeated exposure	Other lithium ion salts based on highly fluorinated chemicals might be used
Ethylene carbonate (EC) CAS 96-49-1		<b>H302</b> Acute toxicity, oral <b>H319</b> Causes serious eye irritation <b>372</b> Causes damage to organs through prolonged or repeated exposure	
Diethyl carbonate (DEC) CAS 872-36-6		<b>H226</b> Flammable liquid and vapour <b>H315</b> Causes skin irritation <b>H335</b> May cause respiratory irritation <b>H351</b> Suspected of causing cancer <b>H361</b> Suspected of causing cancer	
Vinylene carbonate (VC) CAS 872-36-6		<b>H302</b> Acute toxicity, oral <b>H311</b> Acute toxicity, dermal <b>H315</b> Causes skin irritation <b>H317</b> May cause an allergic skin reaction <b>H318</b> Causes serious eye damage <b>372</b> Causes damage to organs through prolonged or repeated exposure <b>H411</b> Toxic to aquatic life with long lasting effects	



Material/CAS	Chemical formula	Hazard	Comment
Ethyl methyl carbonate (EMC)  CAS 623-53-0		<b>H226</b> Flammable liquid and vapour <b>H315</b> Causes skin irritation <b>H319</b> Causes serious eye irritation <b>H335</b> May cause respiratory irritation	Also commonly used in electrolyte
Dimethyl carbonate (DMC)  CAS 616-38-6		<b>H225:</b> Highly flammable liquid and vapour	Also commonly used in electrolyte
Propylene carbonate (PC)  CAS 108-32-7		<b>H319</b> Causes serious eye irritation	Also commonly used in electrolyte
Polyvinylidene fluoride (PVDF)  CAS 24937-79-9		Inert polymer with low toxicity	Can contain highly fluorinated impurities from production (e.g. PFOA; PFHxA) that are SVHCs (substances of very high concern)
Fluorinated ethylene propylene (FEP) CAS 25067-11-2		Inert polymer with low toxicity (alternative binder)	Can contain highly fluorinated impurities from production (e.g. PFOA; PFHxA) that are SVHCs (substances of very high concern)

## Production and use phase

The unreacted state is more applicable to the production phase of LIBs. PVDF and/or FEP are often used as binders in the cathode paste which is coated on a current collector, often in aluminium (see Figure 2 below). While these fluoropolymers are inert and have a low toxicity (see table 2) they cause large emissions of fluorinated surfactants during their production such as Perfluorooctanoic acid (PFOA) or perfluorohexanoic acid (PFHxA)<sup>10,11</sup>. Some of these surfactants such as PFOA are persistent bioaccumulative and toxic substances (PBT) and are classified as POPs under the Stockholm convention<sup>12</sup>. Impurities of these surfactants can stay in the binder material and get emitted for example during the cathode preparation.

Other hazardous chemicals are part of the electrolyte (table 2). Electrolyte emissions may occur during electrolyte mixing and filling and in connection with the formation (see Figure 2 below). During formation, gas is formed (mainly from electrolyte reduction/oxidation): H<sub>2</sub>, CO, CO<sub>2</sub>, methane, ethane, ethylene, propane, propylene, etc. It is the most safety-critical step during cell manufacturing. Gasses formed during the formation are highly flammable.

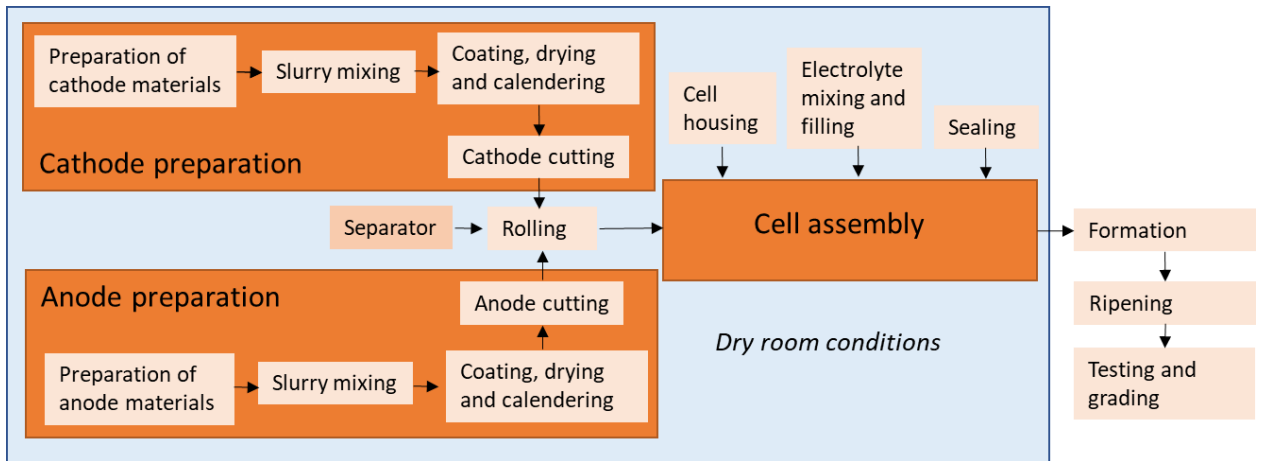


Figure 2. Production of LIB cells, adapted from<sup>13</sup>

Traction battery cells come in three different forms: cylindrical, prismatic or pouch, see Figure 3. Button cells are not used in traction batteries although depicted below.

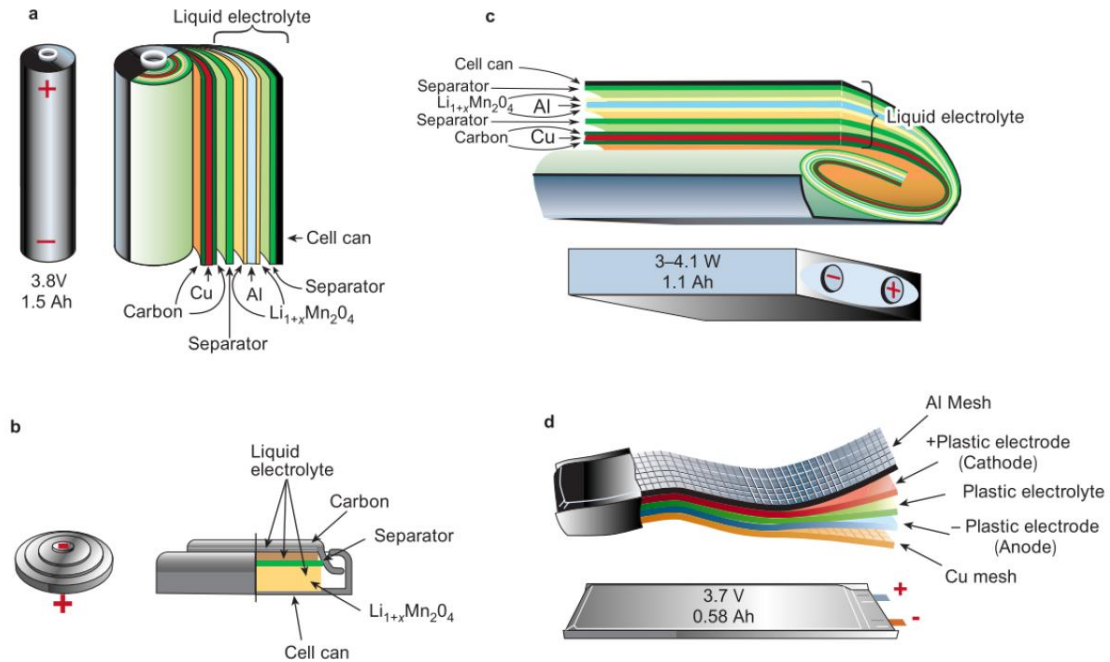


Figure 3 Main construction types of LIB cells: a) wound cylindrical, b) button cell, c) wound prismatic and d) pouch cell <sup>14</sup>

After testing and grading, the LIB cells are shipped as such or built into LIB systems which can comprise hundreds or even thousands of cells in one LIB high-voltage pack. The safety risk of a lithium-ion cell increases with age during operation because the voltage windows in which the electrodes are cycled shift, resulting in a higher possibility that at least one electrode is operated in a meta- or unstable state. Furthermore, higher impedances due to material degradations lead to increasing heat generation and therefore to an increase in the risk of failure<sup>15</sup>. In addition the high voltage of a LIB traction battery pack is a major safety concern throughout its installation and use in a vehicle and entering end-of-life treatment<sup>16</sup>.



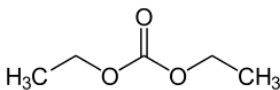
*Figure 4 Lithium ion traction battery pack*

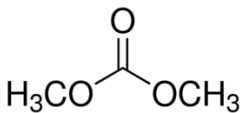
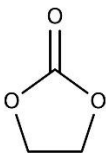
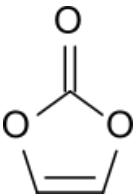
Electrochemical processes during the use of LIBs might also cause the formation of toxic chemicals e.g. in the electrolyte. This can be of high risk if emissions into the environment occur, e.g. through leakage. Especially problematic is an event of a fire caused by e.g. collision of a vehicle. During this process hazardous chemicals will be formed and emitted<sup>16</sup>. Table 3, which shows possible reactions of chemicals in the cells, would then be more applicable than Table 2. The possible formation of hydrofluoric acid (HF) is a major hazard both in the use phase and the ensuing end-of-life phase due to its high toxicity.

Moreover incomplete combustion (temperatures < 850°C) of fluoropolymer cathode materials but also fluorinated ingredients in the electrolyte can lead to the formation of various persistent PFAS<sup>17</sup> (Perfluorinated alkylated substances) contaminants which are problematic when emitted. Reactions are complex and not completely understood<sup>18</sup>. Potential products of the thermolysis of fluoropolymer binder are:

- Short and long chain perfluoroalkyl acids (PFAAs); some of them are POPs and PBT substances. The formation will depend on the electrode binder material (PVDF or FEP)
- Fluorinated gasses such as perfluorinated methane, CF<sub>4</sub>, which is extremely stable in the atmosphere and has a very high global warming potential (4950 kg CO<sub>2</sub>eq/kg)

Table 3 Electrolyte chemicals and binders in LIB cells - potential reactions

Material	Chemical reaction(s)	Hazard	Comment
LiPF <sub>6</sub>	$\text{LiPF}_6 (\text{s}) \leftrightarrow \text{LiF} (\text{s}) + \text{PF}_5 (\text{g})$ $\text{LiPF}_6 + \text{H}_2\text{O} \leftrightarrow \text{LiF} + 2\text{HF} + \text{POF}_3$ $\text{PF}_5 + \text{H}_2\text{O} \leftrightarrow 2\text{HF} + \text{POF}_3$	For HF <b>H300</b> Fatal if swallowed  <b>H310</b> Fatal in contact with skin; Acute toxicity, dermal <b>H314</b> Causes severe skin burns and eye damage <b>H330</b> Fatal if inhaled Acute toxicity, inhalation	
DEC, C <sub>5</sub> H <sub>10</sub> O <sub>3</sub>		<b>H226</b> Flammable liquid and vapour <b>H315</b> Causes skin irritation <b>H335</b> May cause respiratory irritation <b>H351</b> Suspected of causing cancer <b>H361</b> Suspected of causing cancer	Fire hazard; will cause the combustion of other LIB components
PVDF or FEP	$(\text{C}_2\text{H}_2\text{F}_2)_n + \text{fire} \rightarrow \text{HF}$  Incomplete combustion in a fire event may result in persistent contaminants:  → various PFAS → CF <sub>4</sub> (and other)	HF (see above)  For CF <sub>4</sub> ; Half-life (t <sub>1/2</sub> ) in atmosphere= 1000 years Global warming potential (GWP)= 4950  PFAS e.g. PFOA (may be formed during incomplete combustion) <b>H302</b> : Acute toxicity, oral <b>H332</b> : Acute toxicity, inhalation <b>H351</b> : Suspected of causing cancer <b>H360D</b> : May damage the unborn child <b>H362</b> : Reproductive toxicity <b>H372</b> : Specific target organ toxicity, repeated exposure	Binder decomposition:  May decompose to hydrogen fluoride when reaching 400 °C (Nissi 2019);  Formation of PFAS if incomplete combustion at T < 850°C
Lithium ion salts based on highly fluorinated chemicals	Incomplete combustion in a fire event may result in persistent contaminants:  → various PFAS → CF <sub>4</sub> (and other)	see above	Formation of PFAS if incomplete combustion at T < 850°C

Material	Chemical reaction(s)	Hazard	Comment
DMC, C <sub>4</sub> H <sub>8</sub> O <sub>3</sub>		<b>H225:</b> Highly flammable liquid and vapour	Fire hazard; will cause the combustion of other LIB components
EC, C <sub>3</sub> H <sub>4</sub> O <sub>3</sub>		<b>H302</b> Acute toxicity, oral <b>H319</b> Causes serious eye irritation <b>372</b> Causes damage to organs through prolonged or repeated exposure	Complete combustion is likely even under 850 degrees
VC, C <sub>3</sub> H <sub>2</sub> O <sub>3</sub>		<b>H302</b> Acute toxicity, oral <b>H311</b> Acute toxicity, dermal Acute toxicity, dermal <b>H315</b> Causes skin irritation <b>H317</b> May cause an allergic skin reaction <b>H318</b> Causes serious eye damage <b>372</b> Causes damage to organs through prolonged or repeated exposure <b>H411</b> Toxic to aquatic life with long lasting effects	Complete combustion is likely even under 850 degrees

## End-of-life phase

The end-of-life phase can be divided in a first diagnostic and disassembly phase and a second pre-treatment phase according to the figures below.

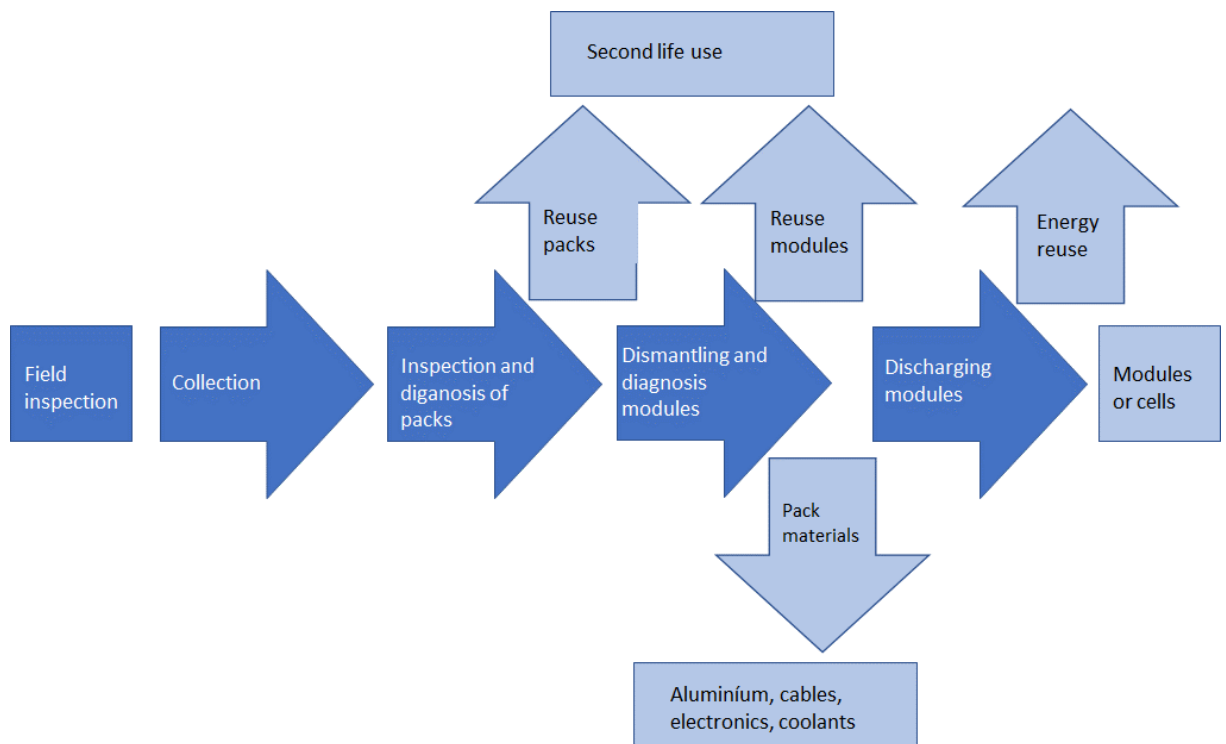


Figure 5. Diagnostic and disassembly phase

The end-of-life phase begins with the battery being unusable in a vehicle. A first action may involve field inspection to decide how to transport the battery pack safely and if its further fate is a second life or material recycling. Transportation of traction batteries are strictly regulated due to safety reasons. Inspection and diagnosis decide the further fate of the battery pack. It may be reused as a pack or as individual modules. Pack materials, around 50% of pack weight, is separated for material recycling. For an undamaged battery pack, safety risks during the first diagnostic and disassembly phase is mainly related to high voltage. After discharging, modules or cells are sent to the ensuing treatment phase.

With regards to the first action, *field inspection*, it is very important that traction battery packs contain the necessary data and information so that it can be handled safely and reused or recycled in the most economical and sustainable way. This data must be accessible to the person(s) carrying out the first inspection. It could be information on chemistry and chemical content, state-of-charge, state-of-health, usage history, automated disassembly, etc.

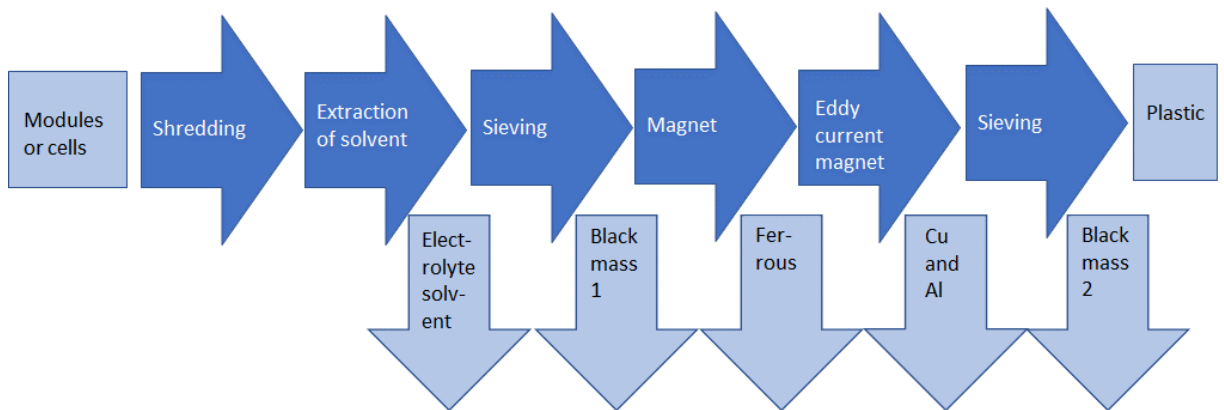


Figure 6. Pre-treatment phase

Modules may or may not be disassembled before treatment. Depending on cell content the shredding often take place in some form of protective environment, e.g. cryogenic for controlling fire hazards. Solvent extraction and recycling are envisioned for future, safe, recycling technologies. After sieving, black mass with or without metals and plastics will be produced and sent for pyrometallurgical and/or hydrometallurgical treatment.

Future recycling may consist of the processes successfully tried in the ReLion project shown below.<sup>19</sup> First de-coking by partial combustion to get rid of the graphite which is an obstacle to down-stream winning of valuable metals. Then pyrometallurgy to win nickel, cobalt and manganese followed by hydrometallurgical winning of lithium, see Figure 7 and Figure 8.

**De-coking by partial combustion**

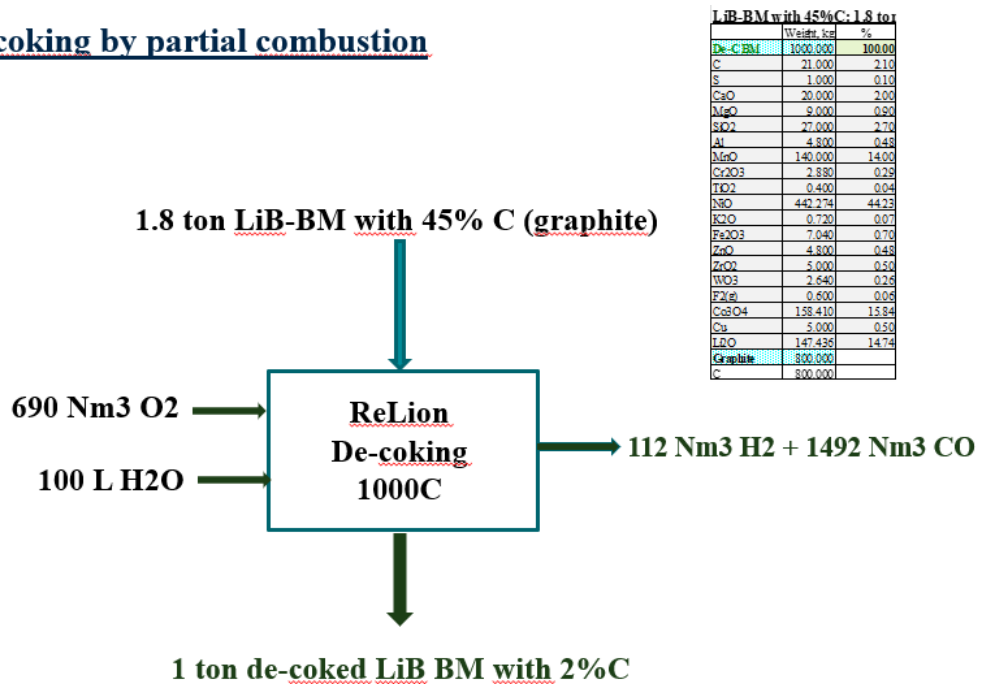


Figure 7. Decoking of black mass as envisioned in the ReLion project<sup>19</sup>



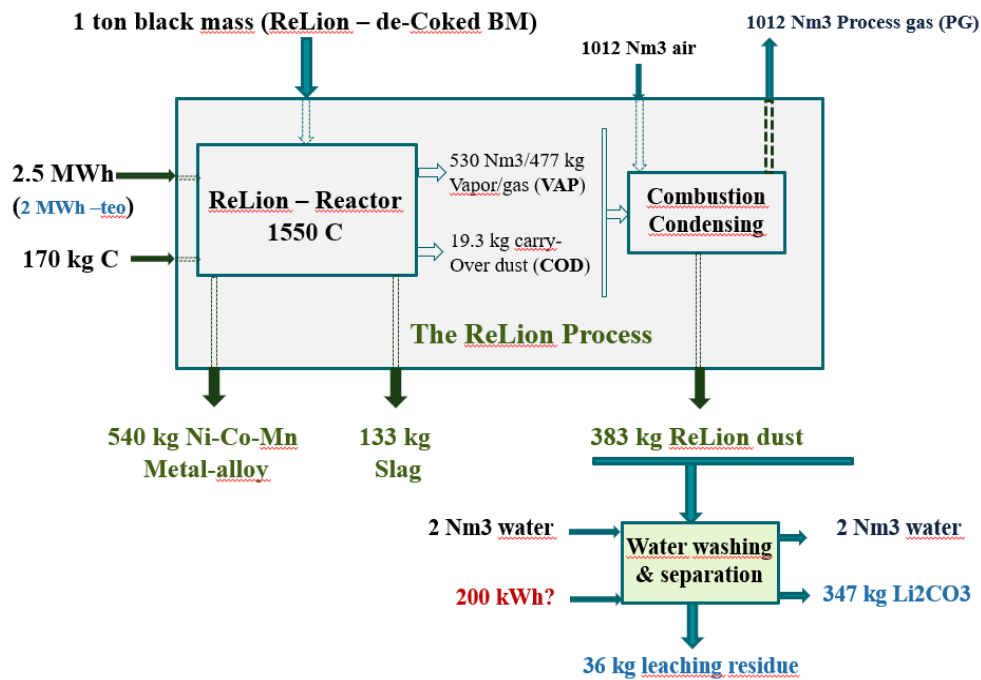


Figure 8. Smelting and lithium separation as envisioned in the ReLion project<sup>19</sup>

While the safety issues of LIBs related to toxicity, fire and explosion and high voltage exist more or less in all life cycle phases, they are more pronounced and have been more investigated in the end-of-life phase<sup>3,20,21</sup>. The main toxicity issue is that the electrolyte containing lithiumhexafluorophosphate,  $\text{LiPF}_6$ , forms hydrogen fluoride. If the temperature during the smelting and lithium separation process (see figure 8) is high enough (e.g.  $1550^\circ\text{C}$ ) all organo fluorine chemicals will be mineralized and it is likely that no PFAS compounds are formed. The formation of HF remains a high risk.

### **$\text{LiPF}_6$ forms hydrogen fluoride and phosphoryl fluoride**

$\text{LiPF}_6$  in the electrolyte is always in equilibrium with the gaseous phosphorus pentafluoride,  $\text{PF}_5$ , via the reaction  $\text{LiPF}_6(\text{s}) \rightleftharpoons \text{LiF}(\text{s}) + \text{PF}_5(\text{g})$ <sup>22</sup>. Both  $\text{LiPF}_6$  and  $\text{PF}_5$  are very sensitive to water, even traces of moisture and forms hydrogen fluoride, HF and phosphoryl fluoride,  $\text{POF}_3$  via the reactions  $\text{LiPF}_6 + \text{H}_2\text{O} \rightleftharpoons \text{LiF} + 2\text{HF} + \text{POF}_3$  and  $\text{PF}_5 + \text{H}_2\text{O} \rightleftharpoons 2\text{HF} + \text{POF}_3$ .

Lebedeva et al<sup>3</sup> found that one cell containing 18-35 g electrolyte, i.e. considerably less than the cell in Table 1, could, in the event of an accidental release form a potentially toxic atmosphere in enclosed spaces. Hydrofluoric acid has serious health hazard having both acute and cumulative toxicity<sup>23</sup>. Larsson et al<sup>21</sup> presents quantitative measurements of heat release and fluoride gas emissions during battery fires for seven different types of commercial lithium-ion batteries. The results showed large amounts of hydrogen fluoride (HF), ranging between 20 and 200 mg/Wh<sup>1</sup> of nominal battery energy capacity. In addition, 15–

<sup>1</sup> 20-200 mg HF per Wh translates to 4-400 g HF per kg cell or 4-400 kg HF per ton cell (with energy density 200 Wh/kg at cell level).

22 mg/Wh of another potentially toxic gas, phosphoryl fluoride ( $\text{POF}_3$ ), was measured in some of the fire tests. Gas emissions when using water mist as extinguishing agent were also investigated. Fluoride gas emission can pose a serious toxic threat and the results are crucial findings for risk assessment and management, especially for large Li-ion battery packs. Fluorine-containing compounds can be present also in the separators and electrode materials<sup>21</sup>. Nissi<sup>23</sup> notes that the PVDF binder material may decompose to hydrogen fluoride when reaching 400 °C. Degradation processes related to PVDF and other fluoropolymers cause the formation of persistent PFAS contamination which is an additional risk.

Hamuyuni et al<sup>24</sup> presents an analysis of the contents and chemistry of the components of the commercially employed electrolytes for lithium-ion batteries revealing that:

- Most currently used lithium-ion battery electrolytes on exposure to the environment are toxic, irritant or harmful in addition to being flammable. While flammability associated risks of electrolytes are well researched and documented such that they are well known by handlers, hazards and risks associated with their toxicity are less often addressed.
- Typical commercial lithium-ion battery electrolyte solvents are volatile, with volatility ranging from moderate to extremely volatile. Several studies have now shown that even small amounts of some of these solvents when exposed to the environment have irreversible serious health effects.
- The reactions of salts including the most commercially successful— $\text{LiPF}_6$ —when in contact with water, for example, is known to result in the generation of gaseous HF, which is very toxic and corrosive compound posing a serious health risk.
- In addition to salts and their resultant toxic products, many of industrial available electrolytes comprise numerous additives which could also be volatile and toxic.

### **Thermal pre-treatment**

Friedrich et al<sup>25</sup> compares four ways of thermal conditioning (pre-treatment) of recycled Li-batteries for safe and highly material efficient processing, see figure below.

Pre-treatment processes: Comparison				
Process	Avoidance potential for toxic gases	Contribution to Resource efficiency	Contribution to Cost efficiency	Benefits for post-processing
Distillation	+++*	+++	o	<ul style="list-style-type: none"> <li>• Safe handling</li> <li>• Possible electrolyte recovery</li> </ul>
Pyrolysis	++	+++	+	<ul style="list-style-type: none"> <li>• Safe handling</li> <li>• Reductive potential in pyrometallurgy (C)</li> <li>• Eased mech. Post processing</li> </ul>
Thermolysis	+++	++	++	<ul style="list-style-type: none"> <li>• Safe handling</li> <li>• No carbon in hydrometallurgy</li> <li>• Eased mech. Post processing</li> </ul>
Combustion	+	+	o	<ul style="list-style-type: none"> <li>• Safe handling</li> </ul>

\*no Thermal Runaway

All thermal pre-treatments allow for flexibility






Figure 9. Four ways of thermal conditioning <sup>25</sup>

Thermal treatment of charged LIBs requires an off-gas treatment system to avoid harmful emissions<sup>20</sup> and to recover electrolyte. According to Pinegar et al<sup>20</sup> LIB electrolyte can be recovered at around 160 °C; temperatures above 200 °C have a higher risk of electrolyte decomposition to CO, CO<sub>2</sub>, and hydrocarbons. Highly toxic or flammable substances such as POF<sub>3</sub>, CF<sub>4</sub>, HF, COF<sub>2</sub>, and C<sub>3</sub>H<sub>4</sub>O also form at temperatures above 200 °C, although some of the generated gases, such as CH<sub>4</sub>, C<sub>2</sub>H<sub>4</sub>, or H<sub>2</sub>, are energetically usable. Some of these gases (e.g. CF<sub>4</sub>) are extremely stable in the atmosphere and have a very high global warming potential as noted above (table 3).

### Summary and recommendations for the end-of-life phase

In the end-of-life phase the risks related to toxicity, fire and high voltage inherent in the traction LIB life cycle become apparent and amplified. LIBs are a green technology but contain different hazardous substances, that can be emitted especially during e.g. fire events. These emissions are of high risks since chemical transformation processes are not well understood so far.

Additional risk occurs during production of raw materials such as highly fluorinated organic chemicals used in LIBs e.g. for binder materials. Due to the electrochemical stability of fluorinated materials their use might be unavoidable to produce batteries with a long life. However, their production, use and disposal need to be controlled. A high temperature treatment in recycling is a possibility to control emissions in the end-of-life phase.

Any laboratory, recycling facility or actor involved in the end-of-life phase of LIBs must carry out risk assessment for their unique activities and equipment and develop and maintain site specific safety protocols for their personal. For inspiration, see for example Nissi<sup>23</sup>.

## Future outlook

Future cell designs may include metallic lithium, which is an acute fire hazard, and/or solid electrolytes, potentially with less acute risks compared to liquid electrolytes. Thus, the safety problems of future lithium cell designs will be different from today's design, but hardly eliminated. Some commercial solid-state lithium batteries and/or lithium metal batteries already exist. At least those containing metallic lithium must be treated separately.

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