# BATTERY DISMANTLING SAFETY PROCEDURES

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REINFORCE

| REINFORCE | |
|---|---|
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| Programme | Horizon Europe |
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| DS – Dassault Systèmes | Beneficiary | Enterprise | FR |
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| ITE – Instituto Tecnológico de la Energía | Beneficiary | RTO | ES |
| TECNALIA | Beneficiary | RTO | ES |
| NUTAI | Beneficiary | Enterprise | ES |
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## Terms and abbreviations

| | |
|---|---|
| EoL | End of Life |
| WP5 | Work Package 5 |
| FMEA | Failure Mode and Effect Analysis |
| RPN | Risk Score |
| FMECA | Failure Mode and Effect Critical Analysis |
| PCB | Printed Circuit Board |

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## 1. Executive summary

The Reinforce project aims to develop and strengthen the circular economy of end-of-life batteries by setting up logistics, diagnostics, sorting, 2nd and 3rd life reuse and recycling circuits. WP5 is focusing on the development of automation and digitalization approaches for the pack-to-module-to-cell-to-electrode disassembly of EoL batteries, as well as with the modelling of an industrial fully automated environment.This document is the first deliverable of the WP5 and highlights the steps for safe dismantling of battery packs, which may require automated actions or special equipment to reduce risks for infrastructure and for people.

Our goal is to create a robust and efficient disassembly process that maximizes material recovery and ensures safety.

The work will begin with the analysis of risks during the disassembly of a pack to a module to a cell. An FMEA will be used to rate these risks and understand how to overcome them. We will then analyze technical solutions to allow the disassembly of a module to a cell in an industrial context, taking into account the constraints of cost, time, and safety. Finally, we'll look at the risks associated with cell-to-electrode disassembly.

## 2. Introduction

In order to assess and clearly identify which step necessitates safety measures during the dismantling process, FMEA has been built and completed. The objective of this FMEA analysis is to identify the risks causing failures during battery pack dismantling and to attribute a quantitative value of this risk, the **Risk Score (RPN)**, allowing criticality comparison of the different steps.

Each step of the dismantling processes has been detailed with their impacts on the product and people.

**How is the Risk Score (RPN) calculated?**

Detectability X Occurrence X Severity = RPN

**Each multiplying factor of the RPN is measured by using the following rating table:**

| LEVEL | Detectability | Occurrence probability | Severity |
|---|---|---|---|
| 1 | Detectable a long time in advance | Rare | No severity |
| **2** | Detectable shortly in advance with possibility of reaction | Low frequency | Low severity |
| **3** | Not detectable in advance with possibility of reaction | Medium frequency | Medium severity |
| **4** | Not detectable in advance without possibility of reaction | High frequency | High severity |

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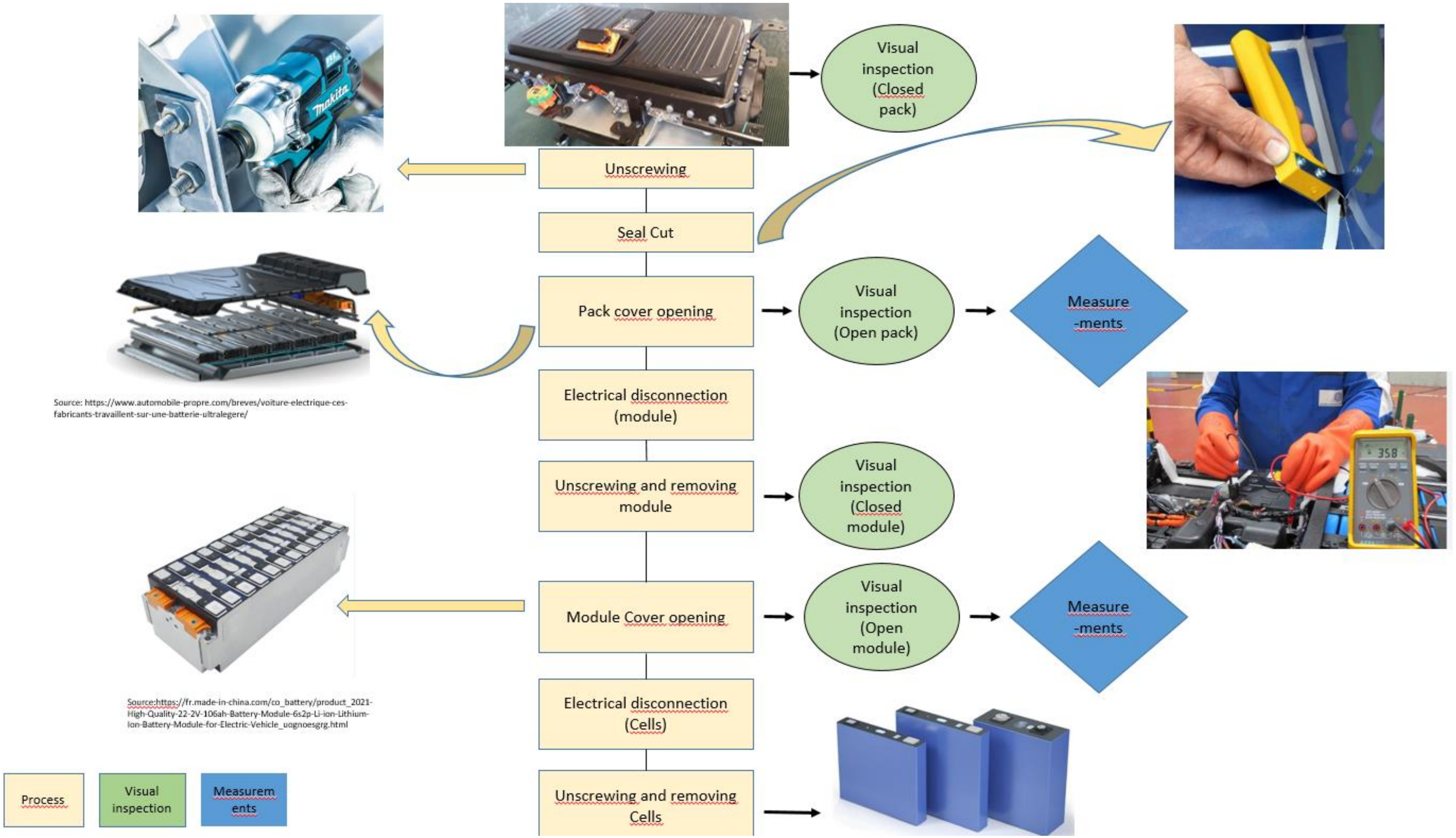


Unscrewing

Seal Cut

Pack cover opening

Electrical disconnection (module)

Unscrewing and removing module

Module Cover opening

Electrical disconnection (Cells)

Unscrewing and removing Cells

Visual inspection (Closed pack)

Visual inspection (Open pack)

Measure -ments

Visual inspection (Closed module)

Visual inspection (Open module)

Measure -ments

Source: https://www.automobile-propre.com/breves/voiture-electrique-ces-fabricants-travaillent-sur-une-batterie-ultralegere/

Source:https://fr.made-in-china.com/co_battery/product_2021-High-Quality-22-2V-106ah-Battery-Module-6s2p-Li-ion-Lithium-Ion-Battery-Module-for-Electric-Vehicle_uognoesgrg.html

| Process | Visual inspection | Measurem ents |
|---|---|---|

Figure 1 : process flow diagram for manual pack-to-module-to-cell dismantling

# 3. FMECA (Failure Modes, Effects and Criticality Analysis) of pack-to-module-to-cell manually dismantled batteries

When an EoL battery needs to be dismantled, the first thought should be to use the BMS data to check the general state of the pack: State of Charge (*SoC*), State of Health (*SoH*), aging, cell voltages, etc. Unfortunately, it is currently very difficult to access BMS data due to manufacturers industrial property rights. This phenomenon is besides clearly observed in the EoL battery packs used in the Reinforce project.

While this problem should be partially solved by the introduction of the Battery Passport (discussed in Task 2.3 of the Reinforce project), it is now crucial to take into account the dismantling of EoL batteries without these data.

→ **The FMEA is built only when the BMS is not accessible as this is what is representative in the project and will be used in the rest of the WP5 task.**

The main risk to be taken into account in the Reinforce project, especially in the part concerning the disassembly of the pack-to-module-to-cell, is the energy remaining in the pack, module and cell.

Indeed, in order to ensure that the modules or cells can be reused in their 2nd or 3rd life, a deep discharge, which would ensure the safety of the disassembly process at all times, is out of the question.

→ **The FMEA is built for the pack-to-module-to-cell disassembly part if a deep discharge has not been carried out.**

| Step | Function | Failure mode | Possible cause of failure | Failure effect | Evaluation | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | D | O | G | C |
| 1 | Visual inspection closed pack on the table | Manufacturinf defect | Separator fault | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 1 | 4 | 16 |
| | | Choc/Vibration | Insulation fault | Electrification, Electrocution | 4 | 2 | 1 | 8 |
| | | | Hot pack | TR, burn | 4 | 1 | 4 | 16 |
| | | | Leak of electrolyte | Toxic gas inhalation | 3 | 2 | 4 | 24 |
| | | Casing integrity | Energized bare part | Electrification, Electrocution | 1 | 2 | 4 | 8 |
| 2 | Unscrewing | Remove mechanical stress | Cover deformation, mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 2 | 4 | 32 |
| 3 | Seal cut | Remove mechanical stress | Cover deformation, mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 2 | 4 | 32 |
| | | | | | 4 | 2 | 4 | 32 |
| | | Lack of knowledge of the pack | Cover deformation, mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 3 | 4 | 12 |
| | | | | Electrification, Electrocution | 1 | 3 | 4 | 12 |
| 4 | Pack cover opening | Mishandling | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 |
| 5 | Visual inspection open pack on the table | Choc/Vibration | Insulation fault | Electrification, Electrocution | 4 | 2 | 4 | 32 |
| | | | Hot pack | TR, burn | 2 | 1 | 4 | 8 |
| | | | Leak of electrolyte | Toxic gas inhalation | 1 | 2 | 4 | 8 |
| | | Mishandling | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 |

*Table 1: FMEA for manual EoL battery disassembly pack-to-module-to-cell (1/3)*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 6 | **Measurements** | Mishandling | Unsuitable tools | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 2 | 4 | 8 |
| | | | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 |
| | | | Unsuitable measures | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 2 | 4 | 32 |
| 7 | **Electrical disconnection** | Mishandling | Unsuitable tools | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 2 | 4 | 8 |
| | | | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 |
| | | | Lack of operator training | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 1 | 4 | 4 |
| | | Choc/Vibration | Mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 2 | 2 | 4 | 16 |
| 8 | **Unscrewing and removing module** | Mishandling | Energized bare part | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 2 | 4 | 8 |
| | | | | Electrification, Electrocution | 1 | 2 | 4 | 8 |
| | | | Module fall | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 1 | 4 | 16 |
| | | | | Technicien injury | 4 | 1 | 4 | 16 |
| | | Module integrity degradation | Swelling | Impossible to unscrew and remove the module | 1 | 2 | 1 | 2 |
| | | | Fastener oxidation | Impossible to unscrew and remove the module | 1 | 1 | 1 | 1 |
| 9 | Visual inspection closed module on the table | Manufacturing defect | Separator fault | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 1 | 4 | 16 |
| | | Choc/Vibration | Insulation fault | Electrification, Electrocution | 4 | 2 | 1 | 8 |
| | | | Hot module | TR, burn | 4 | 1 | 4 | 16 |
| | | | Leak of electrolyte | Toxic gas inhalation | 3 | 2 | 4 | 24 |
| | | Casing integrity | Energized bare part | Electrification, Electrocution | 1 | 2 | 4 | 8 |
| 10 | **Module cover opening** | Remove mechanical stress | Cover deformation, mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 2 | 4 | 32 |
| | | Mishandling | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 |
| 11 | **Visual inspection open module on the table** | Choc/Vibration | Insulation fault | Electrification, Electrocution | 4 | 2 | 4 | 32 |
| | | Mishandling | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 |

*Table 2: FMEA for manual EoL battery disassembly pack-to-module-to-cell (2/3)*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 12 | Measurements | Mishandling | Unsuitable tools | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 2 | 4 | 8 |
| | | | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 |
| | | | Unsuitable measures | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 2 | 4 | 32 |
| 13 | Electrical disconnection (PCB + cells) | Mishandling | Unsuitable tools | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 2 | 4 | 8 |
| | | | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 |
| | | | Lack of operator training | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 1 | 4 | 4 |
| | | Choc/Vibration | Mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 2 | 2 | 4 | 16 |
| 14 | Unscrewing and removing cells | Mishandling | Energized bare part | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 2 | 4 | 8 |
| | | | | Electrification, Electrocution | 1 | 2 | 4 | 8 |
| | | | Cell fall | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 1 | 4 | 16 |
| | | | | Technicien injury | 4 | 1 | 4 | 16 |
| | | | Unsuitable tools | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 2 | 4 | 8 |
| | | Cell integrity degradation | Swelling | Impossible to unscrew and remove the module | 1 | 2 | 1 | 2 |
| | | | Fastener oxidation | Impossible to unscrew and remove the module | 1 | 1 | 1 | 1 |

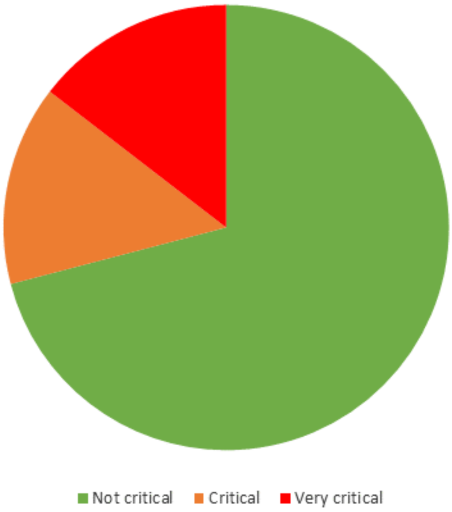
*Table 3: FMEA for manual EoL battery disassembly pack-to-module-to-cell (3/3)*

## FMEA analysis

- Process flow details: 14 steps
- Failure mode analysis: 16 failure mode – 20 possible causes

→ **Level at which action must be taken, defined as the criticality threshold: 32**
Beyond this threshold, the effect of the failure is not bearable. Action is needed.

- RPN distribution: 15% as very critical (red); 15% are ranked as critical (orange) and 70% as non-critical (green).



The very critical stages (in red in Table 1) and critical stages (in orange in Table 1) are:

2. Unscrewing
3. Seal cut
4. Opening the pack cover
5. Visual inspection of the opened pack
6. Measurements
7. Modules electrical disconnection
10. Module cover opening
11. Visual inspection of the open module
12. Measurements
13. Cells + PCB Electrical disconnection

It is important to notice that almost all the dismantling stages present **at least a critical risk (10/14)**, and that the main cause of these risks is the fall of a part due to incorrect handling, resulting in the drop of an instrument.

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## 4. Reducing criticality of the pack-to-module-to-cell disassembly

| Step | Function | Failure mode | Possible cause of failure | Failure effect | Evaluation |  |  |  | Preventive action | Update |  |  |  | *Comments* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | D | O | G | C |  | D | O | G | C |  |
| 1 | Visual inspection closed pack on the table | Manufacturinf defect | Separator fault | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 1 | 4 | 16 |  |  |  |  |  | *Gas release*<br>*Increase of temperature*<br>*Maybe flash light*<br>*Maybe sound of explosion*<br>*Maybe over-pressure*<br>*Maybe fire* |
|  |  | Choc/Vibration | Insulation fault | Electrification, Electrocution | 4 | 2 | 1 | 8 |  |  |  |  |  |  |
|  |  |  | Hot pack | TR, burn | 4 | 1 | 4 | 16 | Thermal camera | 1 | 1 | 4 | 4 |  |
|  |  |  | Leak of electrolyte | Toxic gas inhalation | 3 | 2 | 4 | 24 | VOC measurment | 1 | 2 | 4 | 8 |  |
|  |  | Casing integrity | Energized bare part | Electrification, Electrocution | 1 | 2 | 4 | 8 |  |  |  |  |  |  |
| 2 | **Unscrewing** | Remove mechanical stress | Cover deformation, mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 2 | 4 | 32 | PPE, personnel authorization | 4 | 2 | 3 | 24 | *If impossible : recycling or destruction* |
|  |  |  |  |  |  |  |  |  | **Action performed by a robot** | 4 | 2 | 1 | 8 |  |
| 3 | **Seal cut** | Remove mechanical stress | Cover deformation, mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 2 | 4 | 32 | PPE, personnel authorization | 4 | 2 | 3 | 24 | *If impossible : recycling or destruction* |
|  |  |  |  |  | 4 | 2 | 4 | 32 | **Action performed by a robot** | 4 | 2 | 1 | 8 |  |
|  |  | Lack of knowledge of the pack | Cover deformation, mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 3 | 4 | 12 | **Action performed by a robot** | 1 | 3 | 1 | 3 |  |
|  |  |  |  | Electrification, Electrocution | 1 | 3 | 4 | 12 | **Action performed by a robot** | 1 | 3 | 1 | 3 |  |
| 4 | **Pack cover opening** | Mishandling | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 | **Action performed by a robot** | 4 | 1 | 1 | 4 | *If impossible : recycling or destruction* |
| 5 | **Visual inspection open pack on the table** | Choc/Vibration | Insulation fault | Electrification, Electrocution | 4 | 2 | 4 | 32 | PPE, personnel authorization, measurments | 1 | 2 | 4 | 8 | *If impossible : recycling or destruction* |
|  |  |  | Hot pack | TR, burn | 2 | 1 | 4 | 8 | Thermal camera | 1 | 1 | 4 | 4 |  |
|  |  |  | Leak of electrolyte | Toxic gas inhalation | 1 | 2 | 4 | 8 | VOC measurment | 1 | 2 | 4 | 8 |  |
|  |  | Mishandling | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 | **Action performed by a robot** | 4 | 1 | 1 | 4 |  |

*Table 2: FMEA for safer EoL battery disassembly pack-to-module-to-cell (1/4)*

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| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | **Measurements** | Mishandling | Unsuitable tools | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 1 | 2 | 4 | 8 | Distinguishing between insulated tools and others | 1 | 1 | 4 | 4 | |
| | | | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 | **Action performed by a robot** | 4 | 1 | 1 | 4 | |
| | | | Unsuitable measures | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 2 | 4 | 32 | Distinguishing between insulated tools and others<br>Double-check | 4 | 1 | 4 | 16 | |
| 7 | **Electrical disconnection** | Mishandling | Unsuitable tools | Internal short circuit inside the cell --> hot point --> termal runaway -- | 1 | 2 | 4 | 8 | Distinguishing between insulated tools and others<br>Double-check | 1 | 1 | 4 | 4 | *If impossible : recycling or destruction* |
| | | | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway -- | 4 | 3 | 4 | 48 | **Action performed by a robot** | 4 | 1 | 1 | 4 | |
| | | | Lack of operator training | Internal short circuit inside the cell --> hot point --> termal runaway -- | 1 | 1 | 4 | 4 | Trained staff | 1 | 1 | 4 | 4 | |
| | | Choc/Vibration | Mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway -- | 2 | 2 | 4 | 16 | **Action performed by a robot** | 2 | 1 | 4 | 8 | |
| 8 | **Unscrewing and removing module** | Mishandling | Energized bare part | Internal short circuit inside the cell --> hot point --> termal runaway -- | 1 | 2 | 4 | 8 | Double-checking | 1 | 1 | 4 | 4 | *If impossible : recycling or destruction* |
| | | | | Electrification, Electrocution | 1 | 2 | 4 | 8 | Double-checking | 1 | 1 | 4 | 4 | |
| | | | Module fall | Internal short circuit inside the cell --> hot point --> termal runaway -- | 4 | 1 | 4 | 16 | **Action performed by a robot** | 4 | 1 | 1 | 4 | |
| | | | | Technicien injury | 4 | 1 | 4 | 16 | **Action performed by a robot** | 4 | 1 | 1 | 4 | |
| | | | | | | | | | PPE (safety footwear) | 4 | 1 | 2 | 8 | |
| | | Module integrity degradation | Swelling | Impossible to unscrew and remove the module | 1 | 2 | 1 | 2 | | | | | | *Do not force the screw : too risky* |
| | | | Fastener oxidation | Impossible to unscrew and remove the module | 1 | 1 | 1 | 1 | | | | | | *Do not force the screw : too risky* |

*Table 2: FMEA for safer EoL battery disassembly pack-to-module-to-cell (2/4)*

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | Visual inspection closed module on the table | Manufacturing defect | Separator fault | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 1 | 4 | 16 | | | | | | |
| | | Choc/Vibration | Insulation fault | Electrification, Electrocution | 4 | 2 | 1 | 8 | | | | | | |
| | | | Hot module | TR, burn | 4 | 1 | 4 | 16 | Thermal camera | 1 | 1 | 4 | 4 | |
| | | | Leak of electrolyte | Toxic gas inhalation | 3 | 2 | 4 | 24 | VOC measurment | 1 | 2 | 4 | 8 | |
| | | Casing integrity | Energized bare part | Electrification, Electrocution | 1 | 2 | 4 | 8 | | | | | | |
| 10 | **Module cover opening** | Remove mechanical stress | Cover deformation, mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 2 | 4 | 32 | PPE, personnel authorization | 4 | 2 | 3 | 24 | *If impossible : recycling or destruction* |
| | | | | | | | | | **Action performed by a robot** | 4 | 2 | 1 | 8 | |
| | | Mishandling | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 | **Action performed by a robot** | 4 | 1 | 1 | 4 | |
| 11 | **Visual inspection open module on the table** | Choc/Vibration | Insulation fault | Electrification, Electrocution | 4 | 2 | 4 | 32 | PPE, personnel authorization, measurments | 1 | 2 | 4 | 8 | *If impossible : recycling or destruction* |
| | | Mishandling | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway --> propagation --> fire and smoke | 4 | 3 | 4 | 48 | **Action performed by a robot** | 4 | 1 | 1 | 4 | |
| 12 | **Measurements** | Mishandling | Unsuitable tools | Internal short circuit inside the cell --> hot point --> termal runaway - | 1 | 2 | 4 | 8 | Distinguishing between insulated tools and others<br>Double-check | 1 | 1 | 4 | 4 | *If impossible : recycling or destruction* |
| | | | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway - | 4 | 3 | 4 | 48 | **Action performed by a robot** | 4 | 1 | 1 | 4 | |
| | | | Unsuitable measures | Internal short circuit inside the cell --> hot point --> termal runaway - | 4 | 2 | 4 | 32 | Single-measurement device<br>Double-check | 4 | 1 | 4 | 16 | |

*Table 2: FMEA for safer EoL battery disassembly pack-to-module-to-cell (3/4)*

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | **Electrical disconnection (PCB + cells)** | Mishandling | Unsuitable tools | Internal short circuit inside the cell --> hot point --> termal runaway -- | 1 | 2 | 4 | 8 | Distinguishing between insulated tools and others<br>Double-check | 1 | 1 | 4 | 4 | *Differentiating between welded and unwelded terminals* |
| | | | Part dropping | Internal short circuit inside the cell --> hot point --> termal runaway -- | 4 | 3 | 4 | 48 | **Action performed by a robot** | 4 | 1 | 1 | 4 | |
| | | | Lack of operator training | Internal short circuit inside the cell --> hot point --> termal runaway -- | 1 | 1 | 4 | 4 | Trained staff | 1 | 1 | 4 | 4 | |
| | | Choc/Vibration | Mechanical movement | Internal short circuit inside the cell --> hot point --> termal runaway -- | 2 | 2 | 4 | 16 | **Action performed by a robot** | 2 | 1 | 4 | 8 | |
| 14 | **Unscrewing and removing cells** | Mishandling | Energized bare part | Internal short circuit inside the cell --> hot point --> termal runaway -- | 1 | 2 | 4 | 8 | Double-checking | 1 | 1 | 4 | 4 | *Differentiating between glued and unglued cells* |
| | | | | Electrification, Electrocution | 1 | 2 | 4 | 8 | Double-checking | 1 | 1 | 4 | 4 | |
| | | | Cell fall | Internal short circuit inside the cell --> hot point --> termal runaway -- | 4 | 1 | 4 | 16 | **Action performed by a robot** | 4 | 1 | 1 | 4 | *If impossible : recycling or destruction* |
| | | | | Technicien injury | 4 | 1 | 4 | 16 | **Action performed by a robot** | 4 | 1 | 1 | 4 | |
| | | | | | | | | | PPE (safety footwear) | 4 | 1 | 2 | 8 | |
| | | | Unsuitable tools | Internal short circuit inside the cell --> hot point --> termal runaway -- | 1 | 2 | 4 | 8 | Distinguishing between insulated tools and others<br>Double-check | 1 | 1 | 4 | 4 | |
| | | Cell integrity degradation | Swelling | Impossible to unscrew and remove the module | 1 | 2 | 1 | 2 | | | | | | *Do not force the screw : too risky* |
| | | | Fastener oxidation | Impossible to unscrew and remove the module | 1 | 1 | 1 | 1 | | | | | | *Do not force the screw : too risky* |

*Table 2: FMEA for safer EoL battery disassembly pack-to-module-to-cell (4/4)*

## 3.1. Through robotization

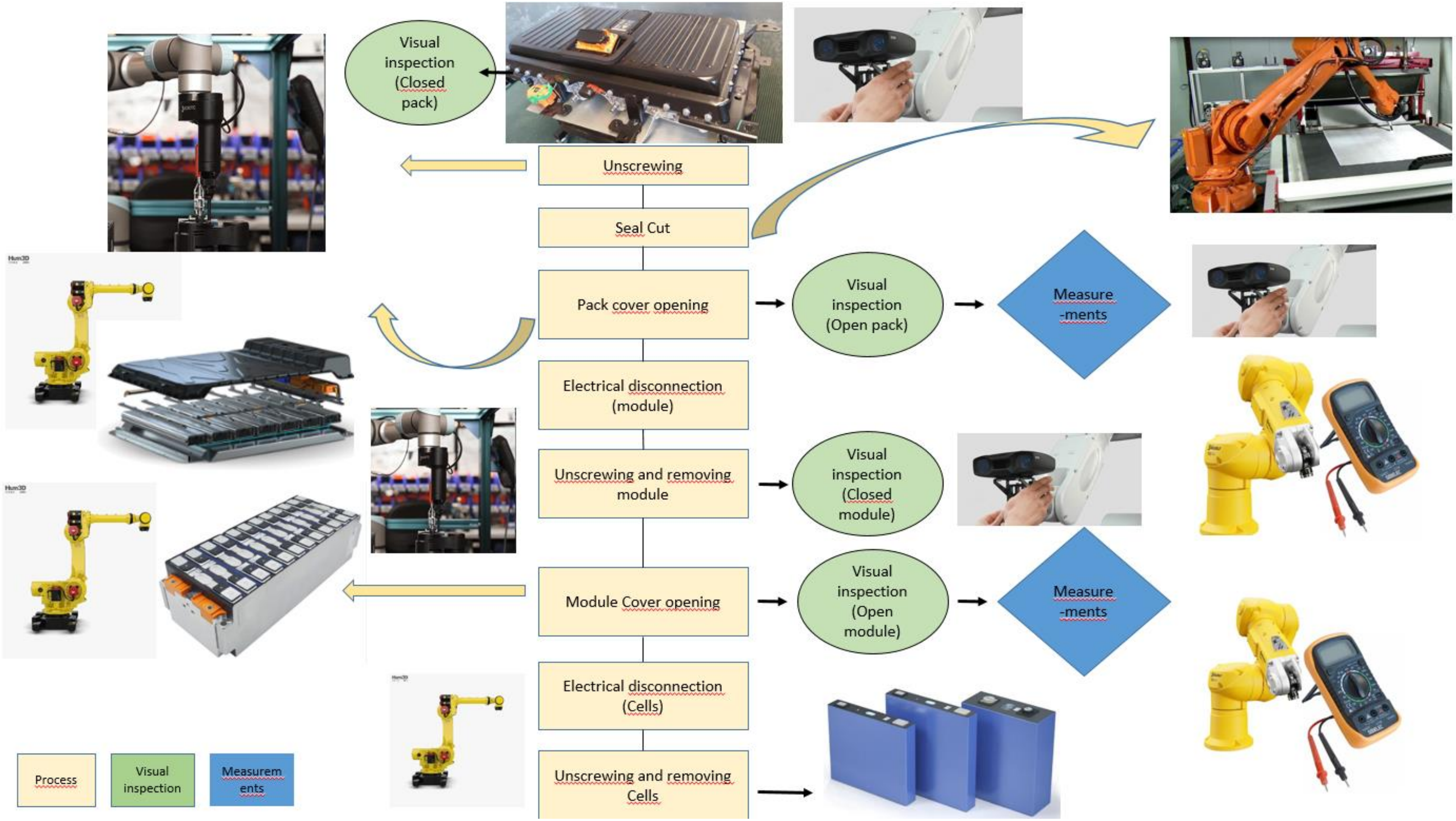

Figure 2 : Process flow diagram for partly robotized pack-to-module-to-cell dismantling

This section focuses on how the criticality of high-risk operations can be reduced by integrating robotic steps throughout the pack-to-module-to-cell disassembly process of an EoL battery.

A general recommendation for the entire disassembly process would be to install the disassembly chain above an effective emergency extinguishing system such as a swimming pool, or to install the EoL battery on an automatic evacuation robot in the event of a thermal runaway event.

Actions that can be carried out by a robot are shown in bold red in Table 2. In detail, these actions and the actions that can be performed by robot are:

1. Unscrewing top casing: The mechanical stress can be handled by robot.

   RPN 32 → RPN 8

2. Seal cut of the pack top casing: The mechanical stress can be removed by robot.

   RPN 32 → RPN 8

3. Pack cover opening: Incorrect handling (especially part dropping) can be avoided by the use of robot.

   RPN 48 → RPN 4

4. Visual inspection of the open pack on the table: The main risk of part-dropping can be dealt with by robot.

   RPN 48 → RPN 4

5. Measurements at pack level: Incorrect handling (especially part-dropping) can be avoided by the use of robot.

   RPN 48 → RPN 4

6. Electrical disconnection of the pack: Incorrect handling (especially part-dropping) can be avoided by the use of robot.

   RPN 48 → RPN 4

7. Unscrewing and removing the module: The fall of a module can be prevented by the use of robot.

   RPN 16 → RPN 4

8. Module cover opening: The use of a robot for this action decreases risks appearing during the removal of the mechanical stress and having a part-dropping during the handling.

   RPN 32 → RPN 8

   RPN 48 → RPN 4

9. Visual inspection of the open module on the table: The main risk of part-dropping can be dealt with by robot.

RPN 48 → RPN 4

10. Measurements at module level: Incorrect handling (especially part-dropping) can be avoided by the use of robot.

RPN 48 → RPN 4

11. Electrical disconnection (PCB + cells): Incorrect handling (especially part-dropping) can be avoided by the use of robot.

RPN 48 → RPN 4

12. Any shock or vibration caused by mechanical movement can also be avoided by robotization.

RPN 16 → RPN 8

13. Unscrewing and removing cells: The fall of a cell can be prevented by the use of robot.

RPN 16 → RPN 4

It is important to note that after the implementation of the robotization actions presented, the residual criticality of the risks never exceeds the value of an RPN of 8, derisking 100% of the stages judged to be very critical and 50% of the critical stages for the pack-to-module-to-cell disassembly process.

## 3.2. Through the use of specific equipment

The four actions of the Table 2, which remain critical after the robotization stage, can be derisked by implementing simple actions:

- systematic use of PPE (Personal Protective Equipment) by trained personnel authorized to access the disassembly line;
- the use of insulated tools;
- double checking of measurements.

Continuous monitoring of the state of the battery can also be carried out using a thermal camera and VOC sensors equipped with an alert system if any anomalies are observed.

## 5. Cell-to-electrode disassembly

The process for safely dismantling a lithium-ion cell and recovering as much active material as possible varies according to the cell format. For example, the disassembly process for a cylindrical lithium-ion cell may be different from that for a pouch or prismatic cell, due to differences in cell design and construction. Each cell format may require specific tools, techniques and safety measures to properly disassemble and recover valuable materials such as lithium, cobalt, nickel and copper.
It is therefore important to take cell format into account when designing a disassembly process, to ensure that it is tailored to the specific needs and characteristics of the cell to be disassembled. This optimizes material recovery and minimizes the safety risks associated with the disassembly process.

The article "A novel mechanical pre-treatment process-chain for the recycling of Li-Ion batteries by Marcello Colledani, Luca Gentilini, Elena Mossali, Nicoletta Picone, presents a novel mechanical pre-treatment process-chain for the recycling of Li-Ion batteries. The pretreatment chain consists of several steps, including battery discharge, cell case cutting, electrolyte capture, mechanical size reduction and sieving. The authors focused on **cylindrical and prismatic formats**.

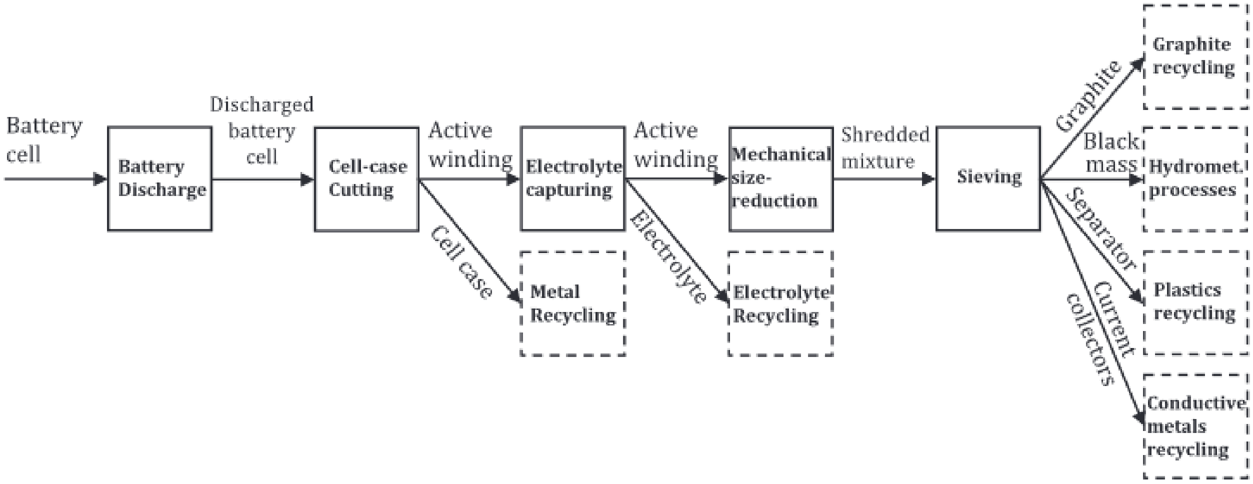

Figure 3*:* Cell-to-electrode disassembly process adapted from[1]

The article related to cell-to-electrode disassembly process entitled as “Disassembly Automation for Recycling End-of-Life Lithium-Ion Pouch Cells” by Liurui Li, Panni Zheng, Tairan Yang, Robert Sturges, Michael W. Ellis, and Zheng Li focuses on the case of **pouch cells format**.

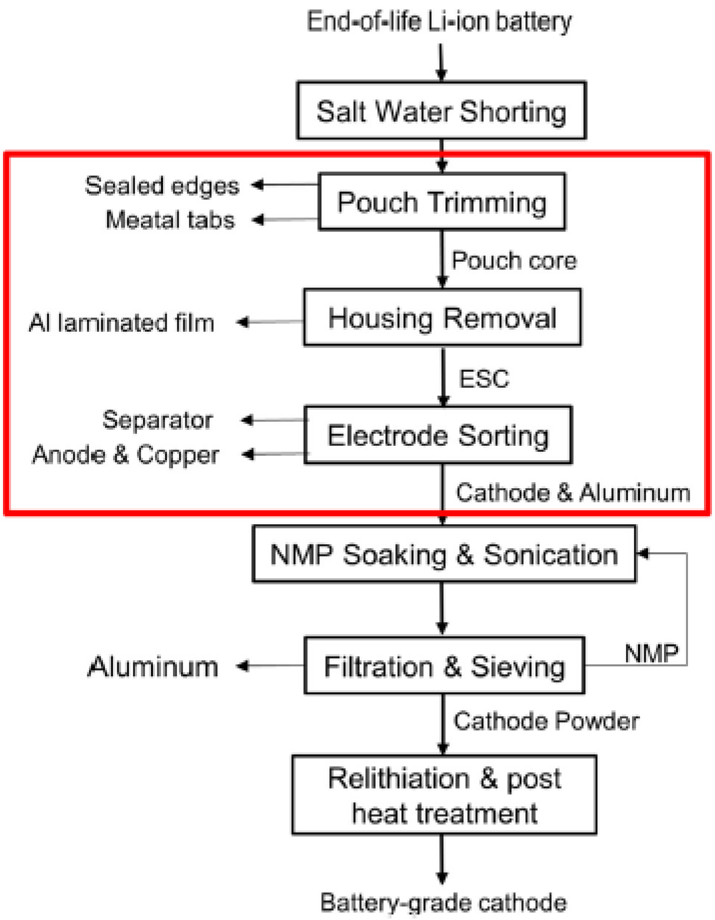

**Figure 4 : Cell-to-electrode disassembly process from [2]**

To start, as mentioned in section 4.2, each step can be made safer by:

- systematic use of PPE (Personal Protective Equipment) by trained personnel authorized to access the disassembly line;
- the use of insulated tools;
- double checking of measurements.

Safety tips for disassembling the electrode cell are detailed step by step below.

# 4. Cell to electrode disassembly

## 4.1. Battery discharge

The first thing to do before dismantling a cell is over-discharge it to be sure there is no residual voltage.

→ This step can be carried out in a fireproof enclosure to prevent any issues in case of a short-circuit or thermal runaway. It could also be processed in a bath of salted water.

## 4.2. Cell case cutting

After the discharge, the next step consists of cutting the cell casing.

→Before starting to cut, a check measurement can be done to be sure if the voltage is 0V.

The cutting method must be adapted to the cell format.

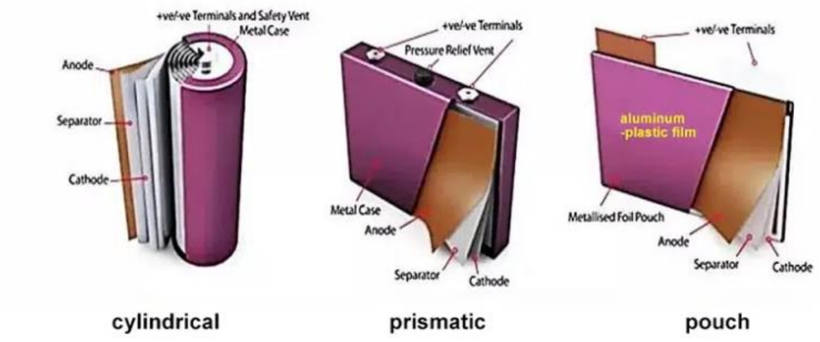

Figure 5 : Cell formats.

- For a **cylindrical cell,** the poles must be firstly removed at first, then the cell should be cut starting from the middle to remove the connections and to limit the loss of active material.

Figure 6 : Cylindrical cell cutting process adapted from[1]

- For **prismatic cells**, the cutting of the poles also takes place before the longitudinal cutting. The connections are removed, and the active material can be preserved.

Figure 7 : Cell cutting process adapted from[1]

- For **pouch cells**, three edges of the housing must be cut off.

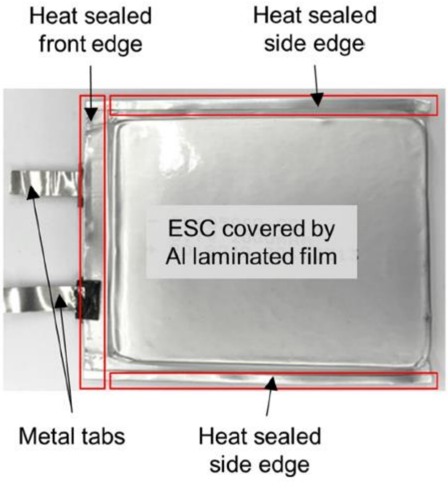

Figure 8 : Pouch cell configuration from [2]

There is a physical injury risk: Dismantling lithium-ion cells may require the use of sharp tools, which can result in physical injuries.
We have seen there are several methods depending on the shape of the casing (cylindrical, prismatic, pouch…).

→ <u>Robots</u> can do this step to limit human risk.

The article "Disassembly Automation for Recycling End-of-Life Lithium-Ion Pouch Cells" by Liurui Li, Panni Zheng, Tairan Yang, Robert Sturges, Michael W. Ellis, and Zheng Li presents an original method for disassembling pouch cells with Z-folded electrodes.

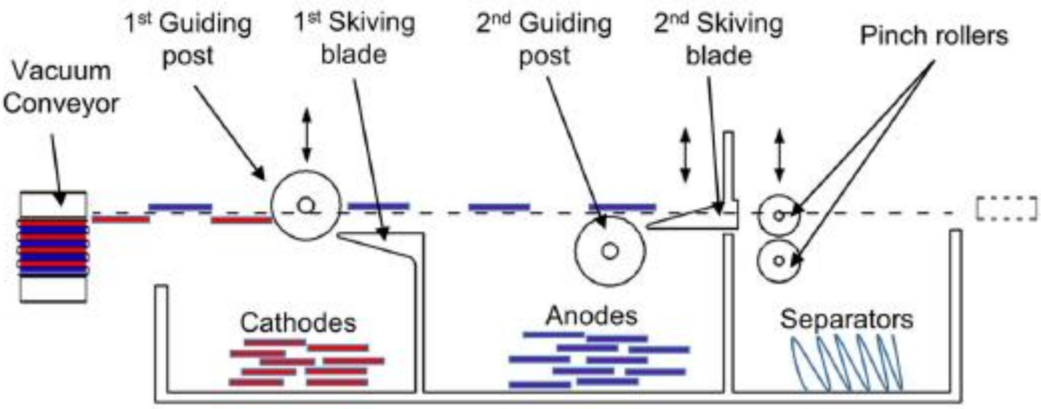

Figure 9 : Pouch cell automatic disassembly from [2]

The cell is first immersed in a saltwater bath and then conveyed to the machine that will cut the packaging to sort the cathode, anode, and separator. This allows for more efficient sorting and a better recovery rate of active materials. This machine makes every step until mechanical size reduction of active materials.

### 4.3. Electrolyte capturing + mechanical size reduction

Damaged or punctured lithium-ion cells can release flammable electrolyte or gases, which may lead to a fire or explosion.

→ In order to have materials dry and clean the case cutting has to be done in active winding.

Once the batteries have been dismantled, they are broken down into smaller components for recycling. This size reduction process facilitates the extraction of valuable materials such as cobalt, nickel and other metals by crushing them into smaller pieces, maximizing the efficiency of the extraction process.

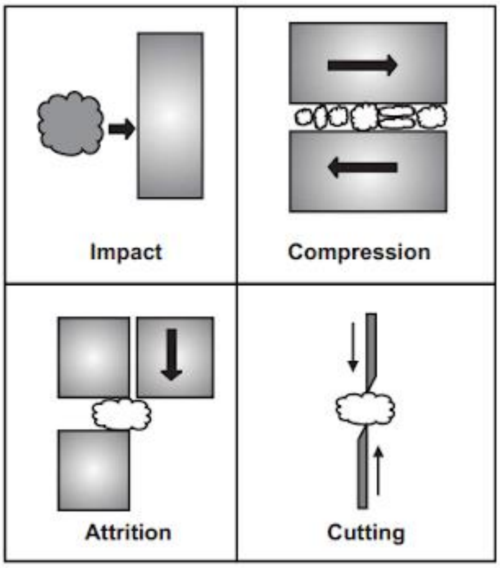

Figure 10 : Mechanical methods of size reduction.

## 4.4. Sieving

The new pre-treatment process chain for recycling of Li-Ion batteries is based on the selective separation of the battery cell case from the active winding, followed by size reduction and dimensional separation. The process chain validation showed significant advantages over existing pre-treatments in terms of homogeneity of output streams and recovery rates of high-value materials.

The article “Direct recycling industrialization of Li-ion batteries: The pre-processing barricade” by Varun Gupta, Maura Appleberry, Weikang Li, Zheng Chen explains that there are three main options for recycling LIBs: pyrometallurgy, hydrometallurgy, and direct recycling. Pyrometallurgy involves smelting techniques similar to mining and results in alloys as products for downstream processing. Hydrometallurgy uses water-based leaching processes to disintegrate material to elemental level and then obtain precursors for cathode material synthesis. Both of these methods currently operate at industrial scale, but involve high energy consumption, high cost, and often only result in recycling the most valuable materials.

In the context of direct recycling, it is essential to understand how the cell component and other impurities can potentially interfere with the regeneration process and lead to low quality electrochemical performance of the product. By assessing the impact and behavior of these impurities, researchers can gain insights into their influence and modify recycling strategies to be more versatile and robust. The pre-treatments we have seen are an essential step in this configuration.

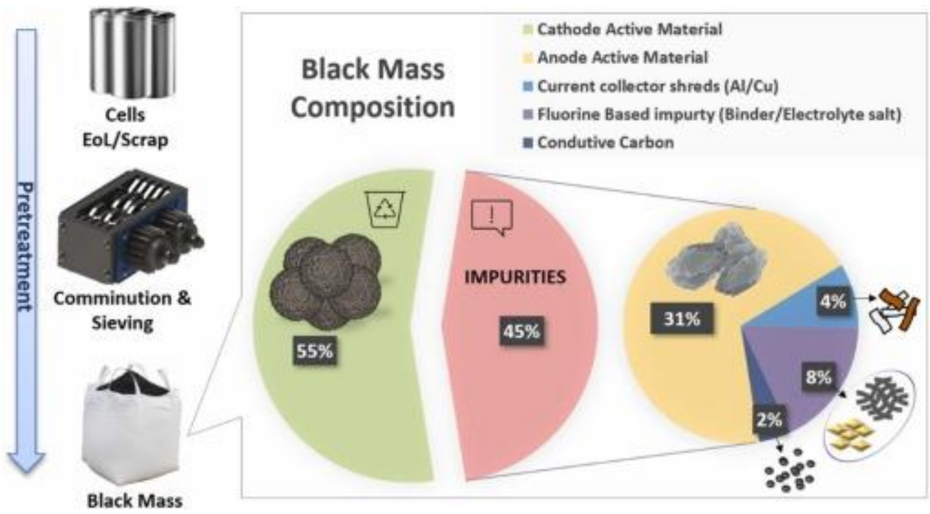

Figure 11 : Typical impurities to deal with after sieving (<100 µm) to obtain feedstock for direct recycling from [2]

There is a risk of exposure to hazardous chemicals: Lithium-ion cells contain hazardous chemicals, such as heavy metals, which can be harmful to human health and the environment if exposed.

→ The separation of materials performed by sieving enables the separation of elements to be recycled and those to be treated before destruction.

## 6. Conclusion

The best way to dismantle an EoL battery safely is to automate the process. It's important to use special equipment that ensures safety, efficiency and precision. Here are some key pieces of equipment to consider:

- Automated dismantling robots: These robots are designed to perform the same movements as a human being, allowing you to work safely and efficiently. They can be programmed to handle different battery types and configurations.

- Vision systems and sensors: Used to identify batteries, check their condition, and guide robots through the disassembly process. Cameras and sensors ensure that components are correctly aligned and positioned.

- Robotic tooling: Includes tools such as screwdrivers, pliers and automated extractors, often mounted on robotic arms. These tools are capable of removing screws, connectors and other fasteners accurately and quickly.

- Automated handling and transport systems: To move dismantled batteries from the dismantling station to other areas of the factory or workshop for recycling or analysis. Conveyors, AGVs (automated guided vehicles) and robotic arms can be used here.

- Safety equipment: Ventilation systems to remove hazardous gases, protective screens, and smoke or leak detection devices are crucial to ensuring a safe working environment when dismantling batteries.

- Monitoring and supervision software: Allows the entire dismantling process to be monitored and controlled. This software can incorporate machine learning algorithms to optimize the process and manage variations in battery types.

- Discharge stations: Before dismantling batteries, it may be necessary to discharge them in a controlled manner to avoid the risk of explosion or fire. These stations enable batteries to be discharged in complete safety.

Easy preventive measures - such as limiting access to the disassembly area and installing thermal sensors and cameras throughout the line - and preventive equipment on which the EoL batteries to be dismantled may be located, also improve the safety of the entire dismantling process.

Regarding the process of disassembling lithium-ion cells to electrode to recover valuable materials, we can say this is a complex and potentially hazardous task that requires:

- careful consideration of cell format,
- use of specific tools and safety precautions.
- The article also emphasizes the need for understanding the impact of impurities on the recycling process and developing upstream processes in parallel to ensure scaling is possible.

We see new approaches to optimize the disassembly process for different cell formats:

- mechanical pre-treatment chain for cylindrical and prismatic cells,
- automated method for disassembling pouch cells with Z-folded electrodes.

These methods aim to improve material recovery and minimize safety risks associated with the disassembly process. The use of personal protective equipment, insulated tools, and double-checking of measurements are also important safety measures that should be systematically implemented. Proper disassembly and recycling of lithium-ion cells can help to reduce waste and minimize the environmental impact of the growing demand for lithium-ion batteries.

## 7. References

[1] “A novel mechanical pre-treatment process-chain for the recycling of Li-Ion batteries” by Marcello Colledani, Luca Gentilini, Elena Mossali, Nicoletta Picone.

[2] “Disassembly Automation for Recycling End-of-Life Lithium-Ion Pouch Cells” by Liurui Li, Panni Zheng, Tairan Yang, Robert Sturges, Michael W. Ellis, and Zheng Li.

[3] “Direct recycling industrialization of Li-ion batteries: The pre-processing barricade” by Varun Gupta, Maura Appleberry, Weikang Li, Zheng Chen.

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