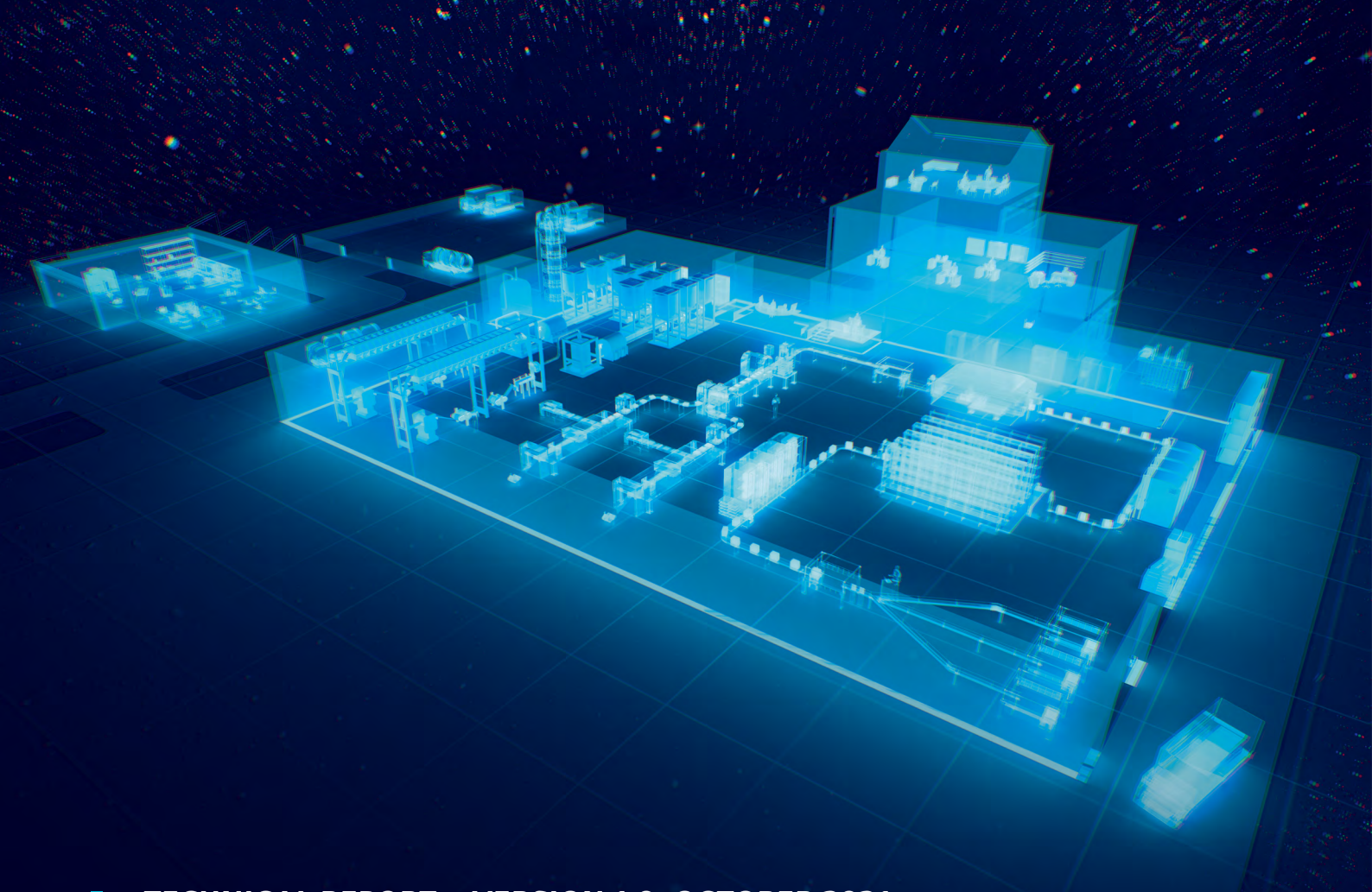


TECHNICAL REPORT – VERSION 1.0, OCTOBER 2021:

Principles for risk-based **fire protection strategies for lithium-ion battery cell production**

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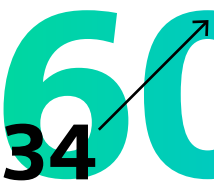
1 Introduction

1.1 Market, Potential and Growth

To be able to meet the rising global demand for renewable, clean and green energy there is currently a very high demand for batteries in general. The focus of the global market is especially on lithium-ion batteries (LIB), as they have advantages over other battery technologies. Some of the advantages of LIB are that they have a very good cycle stability and tend to have a higher energy density as well as lower self-discharge rate than other rechargeable batteries.

In 2019, the Nobel Prize in Chemistry was awarded to John Goodenough, Stanley Whittingham, and Akira Yoshino for their research that led to the development of the LIB. Due to several advantages, as already mentioned, LIB can be used for a wide range of applications such as stationary energy storage systems, in the E-mobility industry and for other transportation means, as well as in consumer electronics such as laptops and cell phones.

Due to the rising need for LIB in the E-mobility industry, namely in Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV), several manufacturers of LIB have started to build factories in close proximity to automotive manufacturers. A few factories are even built by automotive manufacturers themselves. Joint ventures and alliances have also been created to accelerate the speed, especially in Europe.



In 2020, it is estimated that Europe alone will increase its production capacity of LIB from around 34 gigawatt hours (GWh) in 2020, to around 600 GWh in 2030.

+25%

Global battery demand is expected to grow by 25% annually to reach 2,600 GWh in 2030.

1.2 Scope, Restrictions and Legal Fundamentals / Standards

1.2.1. Scope

The report you are about to read is solely focused on the cell production of LIB within the legal framework of Europe with special emphasis on Germany. The target of this report is to provide a comprehensive understanding of the production process of LIB cells, to identify appropriate fire risks and hazards as an input for the risk evaluation of each production step and finally, to present a thorough and generic solution with respect to the structural, technical and organizational fire protection. This report is intended to be used as a guidance for any machine manufacturer, insurance company, owner / investor / operator of a battery factory as well as for any fire protection expert and planning company that would like to ensure personnel safety as well as the protection of buildings and production lines especially in regard to their availability.

During the production process of LIB cells, there are several critical steps in which a fire might occur. One of the most critical occurrences is a LIB cell experiencing some form of abuse. Examples of abuse can include electrical abuse (through over-charging or short-circuit), mechanical abuse (by puncturing) or thermal abuse (by heating-up a battery beyond its design basis temperature). Abuse as such might result in an exothermic process known as “thermal runaway” that can happen if the cell is electrochemically active.

Without any fire protection measures, a thermal runaway could lead to an electrochemical chain reaction with high energy and heat release by means of fire, explosion and toxic gases with a rapid propagation to other LIB cells and / or production parts. This report aims to present all steps in the production process, and then deep dive into the fire safety-critical ones by providing the appropriate fire protection solutions.

The authors and co-authors of this report are Siemens, TÜV SÜD and PEM RWTH Aachen University. Siemens and TÜV SÜD are linked by a long-term cooperation and partnership. Both companies have intensive experience in the field of fire protection and have spent the last couple of years investigating the fire behavior of LIB cells as well as providing and reviewing appropriate fire protection concepts whilst also being pioneers in developing and expanding the state of the art fire protection methods for LIB cell production. PEM at RWTH Aachen University researches and advises on future-oriented issues of electromobility and is one of the market and opinion leading institutes in this sector in Europe.

1.2.2. Restrictions

As already mentioned above, this report only concentrates on the production of LIB cells and does not cover the production and fire protection of LIB modules and packs. Besides the structural, technical and organizational fire protection, the functional / machinery safety as well as the process safety is an important element in the design, commissioning and usage of factories for LIB cell production. The in-depth evaluation and assessment of machinery safety (functional safety) and process safety is out of the scope of this report and has to be realised individually. Furthermore, the report does not cover any explosion protection strategies.

The assessment basis will be a generic “example factory” that produces LIB cells, and which is not related to any specific LIB cell manufacturing company. Additionally, no specific cell chemistry and material is considered, as this report provides guidance on a best practice basis with respect to the steps to be followed when safeguarding a LIB cell production line with special emphasis on the risk evaluation and fire protection.

For each specific production factory for LIB cells, it is recommended to examine and assess the fire behavior of the cell chemistry individually by means of experimental testing and thus prepare a specific risk evaluation and fire protection concept based on the guidance of this report. Siemens, TÜV SÜD and PEM at RWTH Aachen University can support and help with services such as experimental testing of LIB cells (fire / explosion behavior, thermal runaway), reviewing of fire protection concepts and design documents as well as evaluating and reviewing documents with respect to the machinery and process safety.

1.2.3. Codes and standards

Worldwide, the LIB cell production is developing and growing on a large scale. In the area of fire protection, specific national as well as international standards for LIB cell factories are currently lacking; hence, the following codes and standards can be seen as guidance concerning solely the fire protection and risk evaluation with regard to the cell production of LIB in Europe. Respective requirements can be adapted to achieve a high safety level while enabling a high practicability for production purposes.

In Europe, no uniform legal regulation exists for structural fire protection; therefore, whilst using the report as a guideline, the applicable national legal requirements of the respective European country, where a LIB cell factory is planned, have to be taken as a basis. With regard to the legal framework in Germany, for example, the following regulations / guidelines and their administrative rules shall be taken into account:

- Model Building Regulation (MBO)
- Model Guideline on Structural Fire Protection in Industrial Buildings (MIndBauRL)
- Model Administrative Rules on Technical Building Regulations (MVVTB)

Since there are currently no sufficient regulations in national standards for fire protection in LIB cell factories, international standards must also be taken into account. Although these standards are not explicit for LIB cell factories, they can be applied as a reference. The following European and international codes and standards should be considered as requirements that can be adapted to the structural fire protection of LIB cell production:

- EN 13501 – Fire classification of construction products and building elements
- VDI 3564 Blatt 1 – Fire protection – Recommendations for high-bay warehouses
- NFPA 855 – Standard for the Installation of Stationary Energy Storage Systems
- FM Global Property Loss Prevention Data Sheets 5-33 – Electrical Energy Storage Systems

Regarding the technical fire protection, the following German and European codes and standards should be applied:

- DIN VDE 0833-2 – Alarm systems for fire, intrusion and hold up – Part 2: Requirements for fire alarm systems
- ISO 7240 – Fire detection and alarm systems
- CEA 4001 – Sprinkler Systems – Planning and Installation
- NFPA 13 – Standard for the Installation of Sprinkler Systems

Additionally, guidelines of the renowned institute for corporate security and safety specialised in fire protection called VdS Schadenverhütung GmbH should be applied:

- VdS 2109 – VdS Guidelines for Water Spray Systems – Planning and Installation
- VdS 2380 – VdS Guidelines for Fire Extinguishing Systems –
  Fire Extinguishing Systems Using Non-liquefied Inert Gases – Planning and Installation
- ISO 14520-13 – Gaseous fire-extinguishing systems –
  Physical properties and system design – Part 13: IG-100 extinguishant
- VdS 3856 – VdS Guidelines for Sprinkler Protection of Lithium Batteries

Concerning the Fire Hazard and Risk Assessment with respect to the appropriate production steps of LIB cells the following code can be applied:

- DIN EN ISO 19353 – Safety of machinery – Fire prevention and fire protection

For the planning and installation of the technical fire protection with regard to the cell production of LIB in Europe, it is recommended that only one or two different types of codes and standards are taken into account; this is to prevent a mixture of different requirements which may appear similar to each other, but the detailed requirements might differ.

Where there exist different stand-alone systems, e.g., gas extinguishing systems and sprinkler systems, different standards can be applied.

In addition to national building codes, insurers may impose additional requirements for the application of other technical fire safety standards.

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3 Summary

The fast pace of developments in the field of LIB cell production brings along new tasks in the area of fire protection. High hazard potentials are associated with the manufacture of LIB cells in production facilities. As with other manufacturing processes, the fire hazard potential varies in each step of the manufacturing process.

A risk analysis of production facilities for LIB cells must, in addition to a general fire protection assessment of the production building, specifically focus on the individual process steps of LIB cell production. This report provides an analysis and evaluation of the individual LIB cell process steps, as well as the identification of the individual fire risk potential and the development of a safety strategy for the best possible fire hazard prevention and protection of the manufacturing process.

The analysis of the individual process steps has clearly shown that there are individual areas that are of particular importance in the development of the safety strategy and for which the adoption of tailored protective measures are necessary in order to continuously protect and maintain production.

Before ways of developing the safety strategy could be identified, the classic fire protection categories “Building Safety” and “Machinery Safety” have to be expanded to include the aspects of “Process Safety” and “Operative Fire Safety”, as this is the case for all plants with high-value concentrations and the handling of environmentally hazardous substances.

Figure 1
Fire protection categories



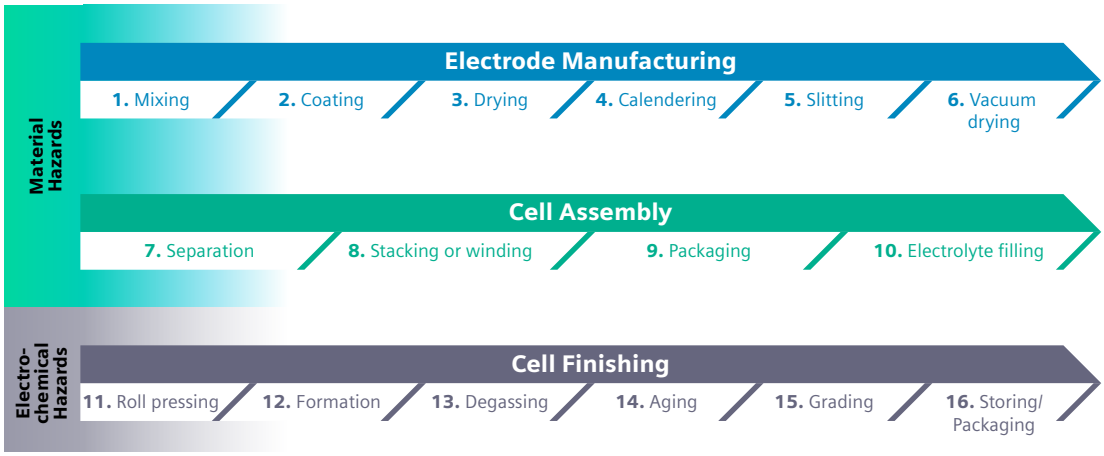
The key in fulfilling these fire protection categories, even for the most critical process steps lies on the one hand in the structural separation (and subdivision) of the critical processes and on the other hand in the early and precise recognition of critical situations and the early and precise introduction of suitable intervention measures. Even the process steps of cell formation and aging, which are identified as the most critical ones, are controllable if a risk-based fire protection concept is implemented.

4 Process description

The process description of the LIB cell production is based on the overview of the PEM RWTH Aachen [L 1] and other references listed in Ch. 7. As this document shall be generally valid, the following description is focused on [L 1] with additional information of other documents specified in the reference list.

The production process of LIB cells can be divided into three high-level process steps, which consist of a total of 16 individual process steps. All these steps are shown in the following Figure 2. Please note that a LIB cell can be produced in three different variants; cylindrical, prismatic or pouch. The process overview in Figure 2 is generic, and it might be the case that not all process steps are applicable for each variant.

Figure 2:
Process overview



From a safety-oriented point of view, the three high-level process steps can be divided into 2 hazard zones:

1. During Electrode Manufacturing and Cell Assembly, there are no electrochemical hazards. Hazards exist due to process steps or intrinsic material properties.
2. During Cell Finishing, the cell is filled with electrolyte and the potential of electrochemical hazards is given.

In the following chapters, the process steps shown in Figure 2 are explained in detail.

4.1 Electrode Manufacturing

Figure 3 shows the process steps for the Electrode Manufacturing. At the end of this process, coils with materials for the cathode and anode for the ongoing process are available.



Figure 3:
Overview of the process Electrode Manufacturing

4.1.1 Mixing

At the beginning, mixtures (slurries) are prepared. One for the anode and one for the cathode. The different slurries consists of active materials (e.g., graphite for the anode, lithium cobalt(III) oxide for the cathode), conductive carbon black, water-based solvents, binders (CMC, carboxymethyl celluloses) and additives (SBR, styrene butadiene rubber). These mixtures are then transported to the coating process step either in pipelines or in atmospherically sealed tanks.

The process is visualized in the following figure. Raw material is added from the containers on the top to the mixing container in the bottom.

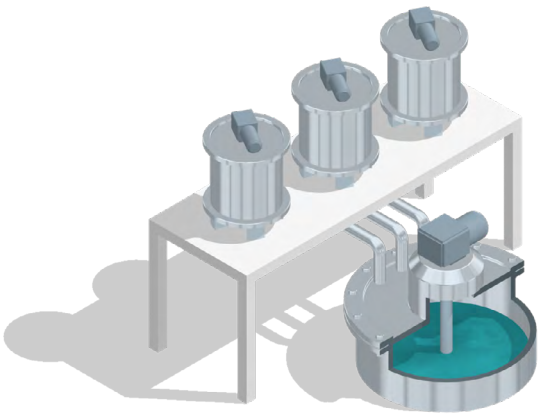


Figure 4:
Mixing

4.1.1.1 Fire Risks and Hazards

Except for the solvent, the substances used are harmless in terms of flammability. An exception is the conductive carbon black, which has an ignition temperature of >500 °C, which is reached by a normal open flame. However, an ignition energy of 1 kJ is required, which is implausible to reach during this process step. Concerning the risk of an explosion, there is a Lower Explosion Level (LEL) of 50 g/m³ [L 1]. If work is carried out under normal circumstances as well as under precision process control and traceability, there are no significant fire risks while mixing (and even less so when transporting the mixture, as the carbon black is then included in the mixture).

4.1.2 Coating

The slurry is transported with containers or pipelines to the coating area. It is applied to a substrate material (carrier foil of aluminium for the cathode and copper foil for the anode) via a coating or printing process. While the foil thickness is between 5 µm and 25 µm depending on the cell design, the foil (coating) width is between 600 mm and 2,200 mm. The most common process is slot die, or as an alternative comma bar.

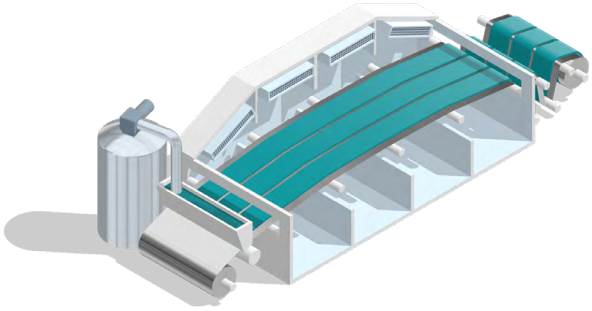


Figure 5:
Coating

4.1.2.1 Fire Risks and Hazards

Based on the flammability of the slurry, mixed in the previous process step, a fire risk cannot be excluded completely. In existing process descriptions ([L 1] & [L 4]), no explicit fire risk or hazard can be found. The only additional substances in this process step are aluminium and copper – an ignition source is not available under normal circumstances.

4.1.3 Drying

According to [L 1], the coated foils are fed into a floatation dryer directly after coating. The floatation dryer is divided into different temperature zones and thus consists of different chambers. During this process, highly flammable solvent residues evaporate and are removed via an exhaust outlet. In the drying process, the foils must pass the process twice since, in some cases, both sides must be coated separately [L 6]. After drying, the foils are cooled down to room temperature.

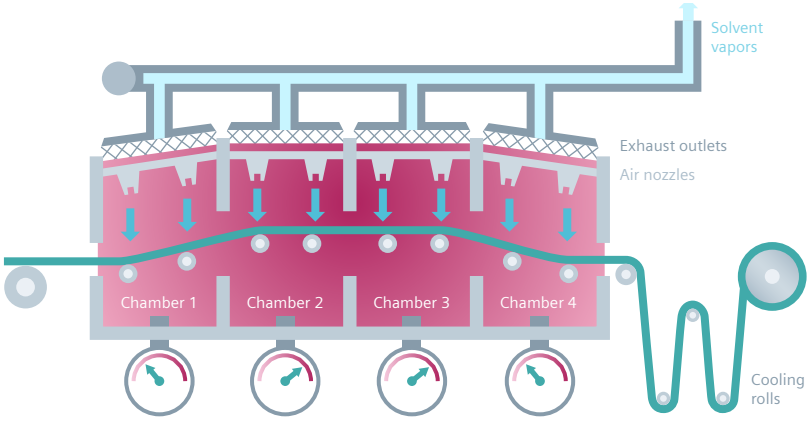


Figure 6:
Drying

Source:
PEM RWTH Aachen University

4.1.3.1 Fire Risks and Hazards

Within this process step there are no risks regarding easily inflammable materials. Nevertheless, as heaters are installed, a thermal input and evaporated solvents are both present; thus, assuming technical defects, it cannot be excluded that an ignition occurs, even if it is very unlikely.

4.1.4 Calendering

After drying, the foils are compressed to create a defined porosity; and are guided through rotating pairs of rollers, matched to the requirements, to achieve the desired compression. After compression, the foils are sent through cleaning rollers (brushes) before being wound / rewound onto a parent coil. The temperature of the rollers can rise up to 150 °C with a temperature control available. A pressure up to 2,500 N/mm² is common with a high precision over the full width of the rolls.

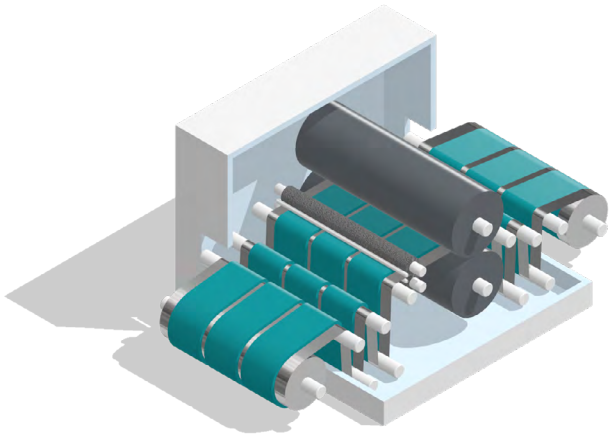


Figure 7:
Calendering

4.1.4.1 Fire Risks and Hazards

As the rollers can be heated, a thermal input is present. A temperature control of the rollers is generally available; however, in the case of a technical defect, a fire risk cannot be excluded completely.

4.1.5 Slitting

The compressed foils are unwound from the parent coil, cut to manageable lengths and rewound onto smaller daughter coils. The cutting can be carried out with a laser or a rolling knife. The cutting width can vary depending on the cell design and lies between 60 mm and 300 mm with a tolerance of +- 150 µm to +- 200 µm. Any waste is removed either by suction or mechanically with a brush. Usually, there is a suction for the cut edge strips. The mechanical cutting speed is between 80 m/min to 150 m/min.

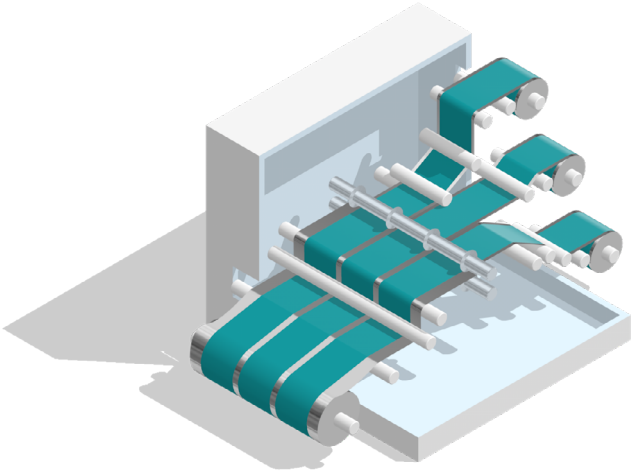


Figure 8:
Slitting

4.1.5.1 Fire Risks and Hazards

During this process step, flammable dusts and vapours occur; generally, they are removed mechanically or by a suction. A risk of fire is low, as ignition is only possible if a technical defect (e.g., failure of suction) occurs.

4.1.6 Vacuum drying

The daughter coils are placed on a coated special goods carrier. The drying of the coils is carried out in a vacuum oven for 12 to 30 hours, removing moisture and solvent. The coils are then transferred to a dryroom. This process is executed before cell assembly.

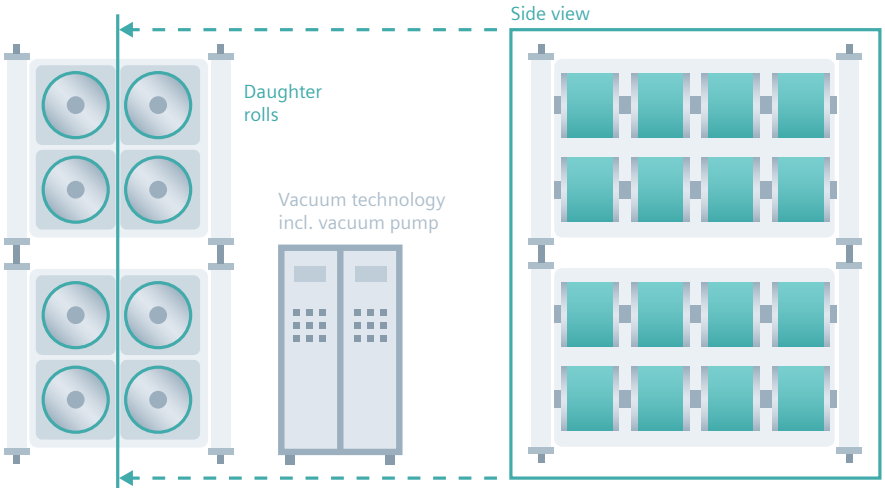


Figure 9:
Vacuum drying

Source:
PEM RWTH Aachen University

4.1.6.1 Fire Risks and Hazards

Since during this process step no mechanical or electrical impact on the coils is existent, there is no risk arising from the coils. Fire risks can be introduced by the vacuum technology, especially hot-running vacuum pumps and control technology, but this risk can be rated as very low.

4.2 Cell Assembly

Figure 10 shows the process steps for the Cell Assembly. At the end of this process the cells are filled with electrolyte and are potentially electrochemically active.



Figure 10:
Overview of the process Cell Assembly

4.2.1 Separation of electrodes

When separating electrodes, the daughter coils are unrolled and cut to the final required formats; this is done either by laser cutting or by punching tools in a continuous process. Basically, the separating process is similar to the slitting process.

The separated sheets are then either fed directly into the next production process step or stored in a magazine. In both, punching and laser cutting, an uncoated edge area remains on the sheet so that a contact lug can be welded on later.

Usually, this process is considered as a separate process, sometimes it is performed together with the stacking or winding process. Please note that this section as well as Figure 11 only refer to the assembly of a pouch cell or stacked prismatic cell.

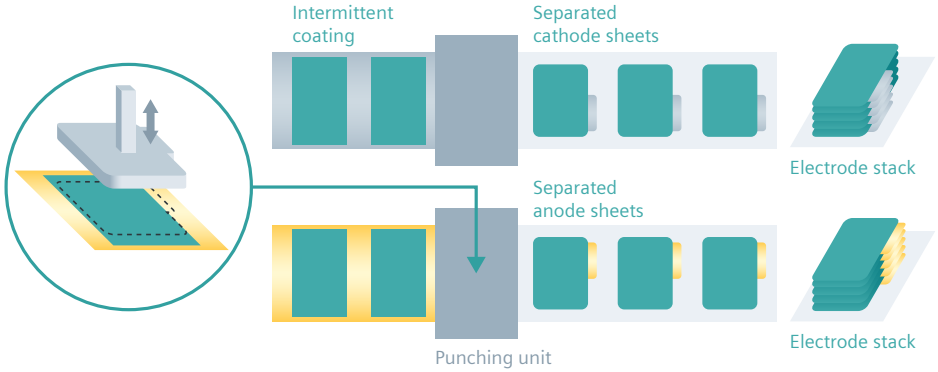


Figure 11:
Separation of electrodes

Source:
PEM RWTH Aachen University

4.2.1.1 Fire Risks and Hazards

During this process step, flammable dusts and vapours occur; usually, they are removed mechanically or by a suction. The risk of a fire is low as an ignition is only possible if a technical defect (e.g., failure of suction) occurs.

4.2.2 Stacking or winding

In stacked cells, individual sheets of cathode and anode are stacked alternately with a separator foil. According to [L1], in case of the z-folding process the separator is an endless foil, while in case of a single stacking process the separator is a single sheet. In a cylindrical cell, the anode foil, separator, cathode foil and another separator are placed on top of each other and wound over a core to form a jelly roll.

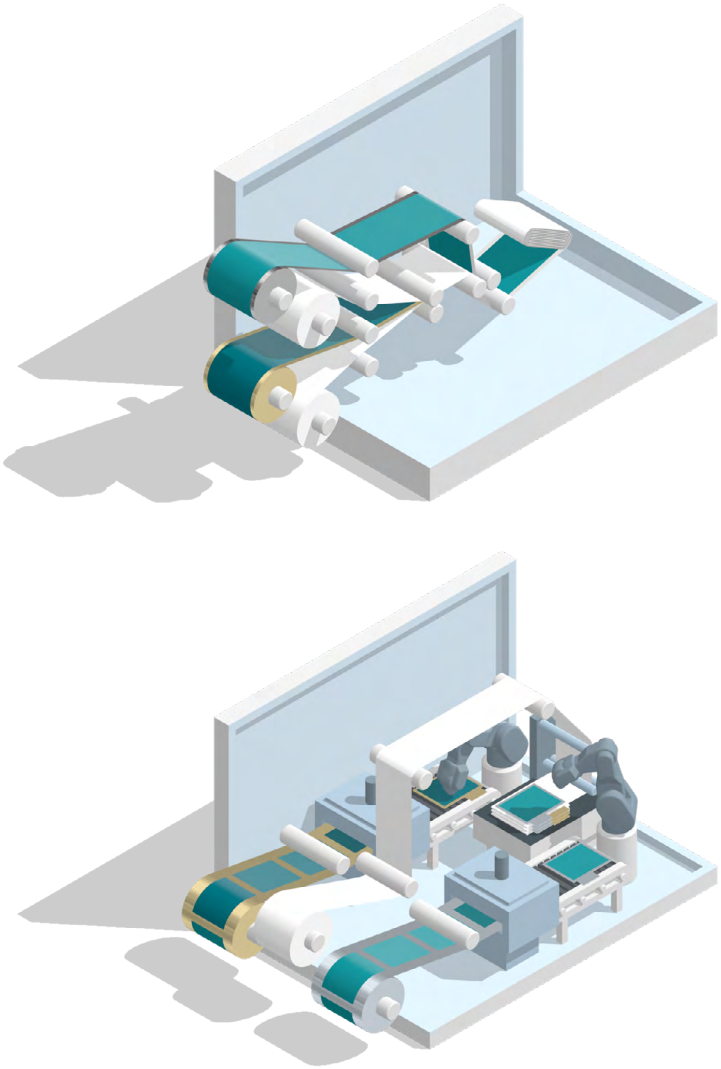


Figure 12:
Winding (top) and stacking (bottom)

4.2.2.1 Fire Risks and Hazards

Usually, the avoidance of electrostatic charging in the winding process is implemented; although this is done for quality reasons, a risk of ignition of available dusts cannot be excluded. Another risk that needs to be considered is an overheating of the rolls.

Though the risks in this process seem to be controllable and negligible, it has to be mentioned that mistakes made in these processes (e.g., damaging the separator) will have a major influence on increasing the risk during the formation process step.

4.2.3 Packaging

Contacts are welded (ultra-sonic) to the finished stacks, or jelly rolls, before they are inserted into the cell housing (pouch, cylindrical, or prismatic hard cases). The cells are sealed by means of impulse or heat contact (pouch cell) or laser welding (prismatic cell). In some cases, one side of the cell is not sealed in order to fill the cell with electrolyte in the next process step, and to make it possible to remove gases after the first charge and discharge of the cell. It is important to avoid damages and that the closure is made leakage free after the degassing process.

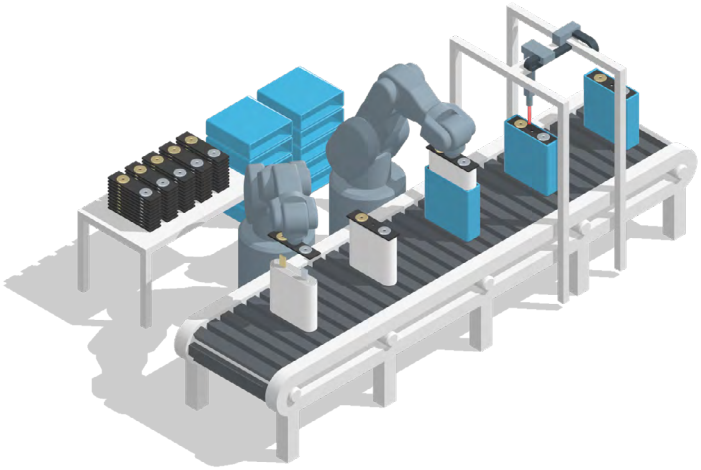


Figure 13:
Packaging

4.2.3.1 Fire Risks and Hazards

Within this process there are several inputs of energy due to the welding processes, thus a fire risk cannot be excluded completely. More important than the fire risks during this process step are the potential procedural errors that may cause or increase fire risks in upcoming processes.

4.2.4 Electrolyte filling

While the cells are filled with electrolyte they are charged alternately with vacuum and argon (to improve the wetting). The purpose of the alternate vacuuming (wetting) is that the electrolyte is distributed better and faster when the capillary effect in the cells is activated. The cell, i.e., the filling opening, is sealed at the end under vacuum.

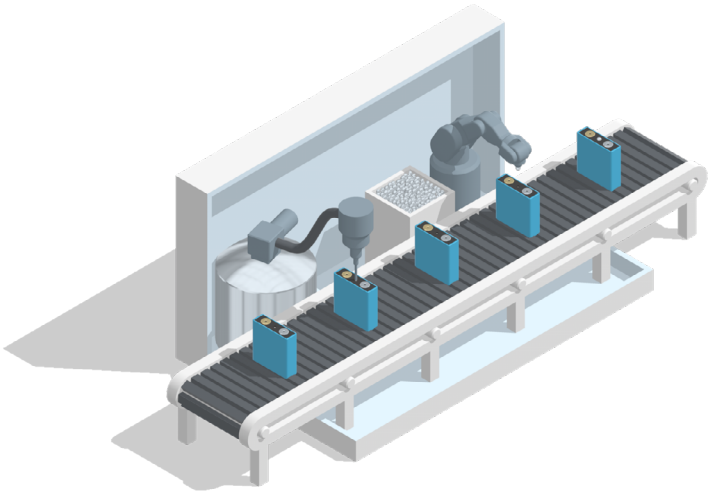


Figure 14:
Electrolyte filling

4.2.4.1 Fire Risks and Hazards

A fire risk is given due to the electrolyte, which is flammable. At the end of the filling process, the filling opening is welded, which comes along with a thermal input and thus increases the risk. As the cell is not yet charged, there is no additional electrochemical risk.

4.3 Cell Finishing

Figure 15 shows the process steps for the Cell Finishing. At the end of this process the cells are completed and ready for shipping.



Figure 15:
Overview of the process
Cell Finishing

4.3.1 Roll pressing (only relevant for pouch cells)

For pouch cells the optional process step roll pressing can be performed. This ensures an optimum distribution of the electrolyte under defined pressure. While the pouch cells are pressed, the rollers are cleaned by secondary cleaning rollers simultaneously.

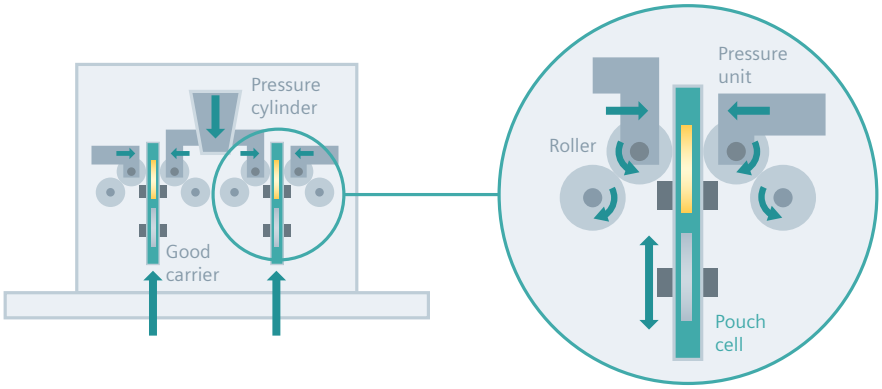


Figure 16:
Roll pressing

Source:
PEM RWTH Aachen University

4.3.1.1 Fire Risks and Hazards

Fire risk can arise due to hot rollers or hot servo motors and the simultaneously presence of electrolyte. As the cells are not electrochemically active in this process step and there is no heat impact or other ignition source, the fire risks are medium.

4.3.2 Formation

The process parameters of formation are very important for the cell manufactures and thus the formation procedures are normally not shared in public. Depending on the cell format it can be generally stated, that the formation starts with a pre-charging step, followed by full charge and discharge cycles. Depending on the cell manufacturer there are different techniques like charging to a specific state of charge (SoC) or pulse charging.

While charging for the first time, the solid electrolyte interphase on the anode is built up. This layer is highly important for the functionality and the quality of the finished cell. Defects can be identified via voltage measurement.

The formation process for LIB cells usually takes several days or longer. During this process, the cells are stored in a high-bay storage system or in containers and applied with a current. The manufactured cells are charged and discharged several times. The formation process is necessary to form a stable and efficient solid electrolyte interphase at the anode at low potentials vs. Li/Li+ to prevent irreversible consumption of electrolyte and lithium-ions. An analogous layer, the so-called cathode-electrolyte interlayer is formed at the cathode at high potentials vs. Li/Li+. These formation processes lead either to lower production rates or to high investment costs due to high space requirements or machinery costs. The formatted cells are placed automatically into stacks and will stay there up to 15 days.

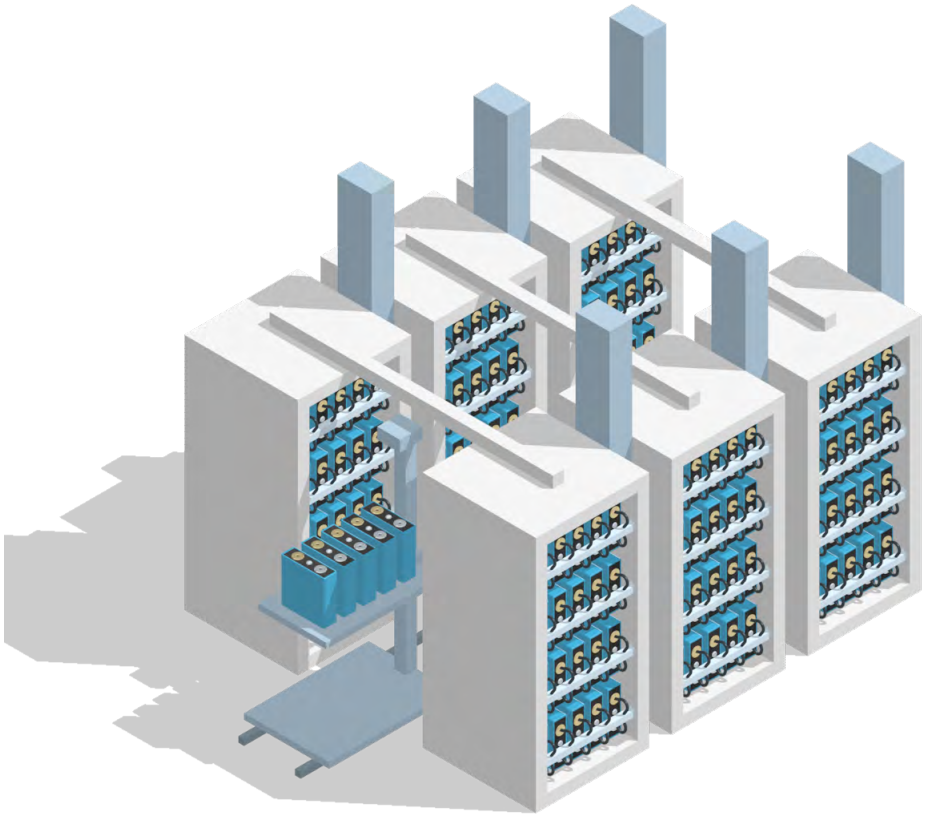


Figure 17:
Formation

4.3.2.1 Fire Risks and Hazards

With the start of the first charging cycle, production errors in previous process steps can have an effect; in particular, the process steps stacking or winding and injecting should be mentioned here. As several cells are charged, and discharged at the same time, there is also an increased risk of fire due to the large quantity of cells. Considering all production processes, the formation process is the one with the highest risk potential, as it is the first time the cells are charged, and discharged, and an electrochemical hazard can be present for the first time.

4.3.3 Degassing (only relevant for pouch and prismatic cells)

The cell is finally sealed at the seam, and a heat input is given. Gas occurring during the formation process is collected in a gas pocket and extracted under vacuum. The gas pocket is separated and later extracted. A sealing seam will remain. Before the gases can be fed into the exhaust system, they must be post-treated, e.g., with a Regenerative Thermal Oxidizer (RTO)

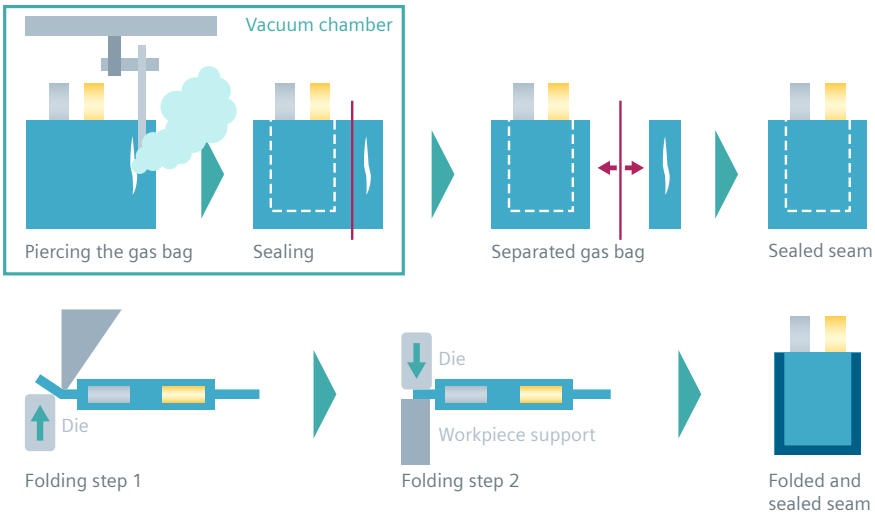


Figure 18:
Degassing

Source:
PEM RWTH Aachen University

4.3.3.1 Fire Risks and Hazards

Due to the sealing process, there is an external input of energy which may lead to an increased risk of fire. If the sealing is not performed with heat, there will still be a fire risk in a charged cell due to material defects, but this should be significantly lower than in the formation process step as defects should have been already identified.

4.3.4 Aging

The aging process represents the final step in cell production and is used for quality assurance. During this process, the cells are stored for a longer time (up to three weeks) in a high-bay storage. Within this process the cells undergo different phases which are separated by temperature, so the cells undergo high temperature (HT) aging and normal temperature (NT) aging.

In [L 1] it is described that during the aging process voltage and impedance measurements are performed regularly at intervals to identify changes in cell properties / performances which are to be detected by regularly measuring the open circuit voltage of the cell over a period of up to three weeks. It is also an option to have no constant monitoring and measurement during the whole aging process, but only at the beginning and the end.

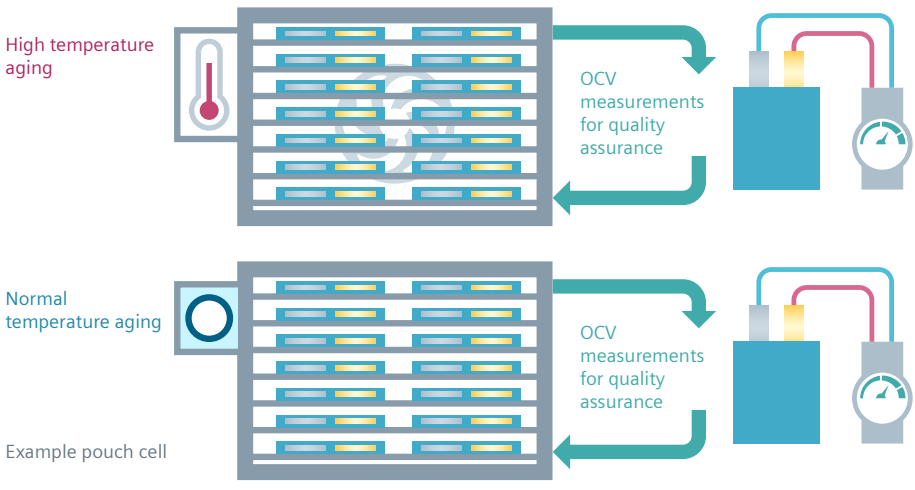


Figure 19:
Aging

Source:
PEM RWTH Aachen University

4.3.4.1 Fire Risks and Hazards

Based on given information, no real-time voltage and impedance measurements are carried out, so a thermal runaway cannot be detected. Obviously, cells with a previous damage may subsequently become conspicuous during the formation process, but there is still a low probability that a cell which has survived the formation process will become conspicuous during the aging process step. Due to the very large quantity of cells in the aging process it exists a considerable risk in this process step.

4.3.5 Grading or End Of Line (EOL) Testing

After the aging process, the cells are transported on a conveyor belt to an end of line (EOL) test station. According to [L 15], the cells are finally checked by further charging and discharging processes, pulse testing and a measuring of the internal resistance; after that they are classified by their quality (e.g., with regard to capacity) and ordered for further use according to the measurement results. In [L 6] a process step “Acceptance Testing” is listed, which is a comparable procedure.

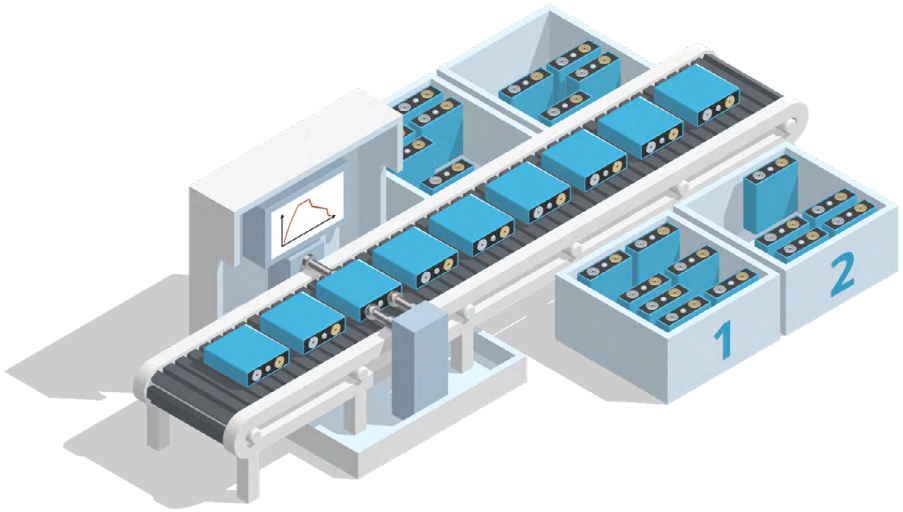


Figure 20:
Grading and EOL Testing

4.3.5.1 Fire Risks and Hazards

The stress resulting from the process and the state of charge is lower than in previous process steps and thus the probability of propagation to other parts of the production line is negligible. Consequently, the risk is lower than in the formation or aging process. Defective cells would have been noticed in the previous process steps and the duration of the grading process is significantly lower compared with the formation or aging process step.

4.3.6 Storing, Packing (and Transport)

The cells are stored in a high-bay storage for shipping, prepared for sale and packed into the shipping department. For the shipping they are packed into plastic and / or cardboard containments.

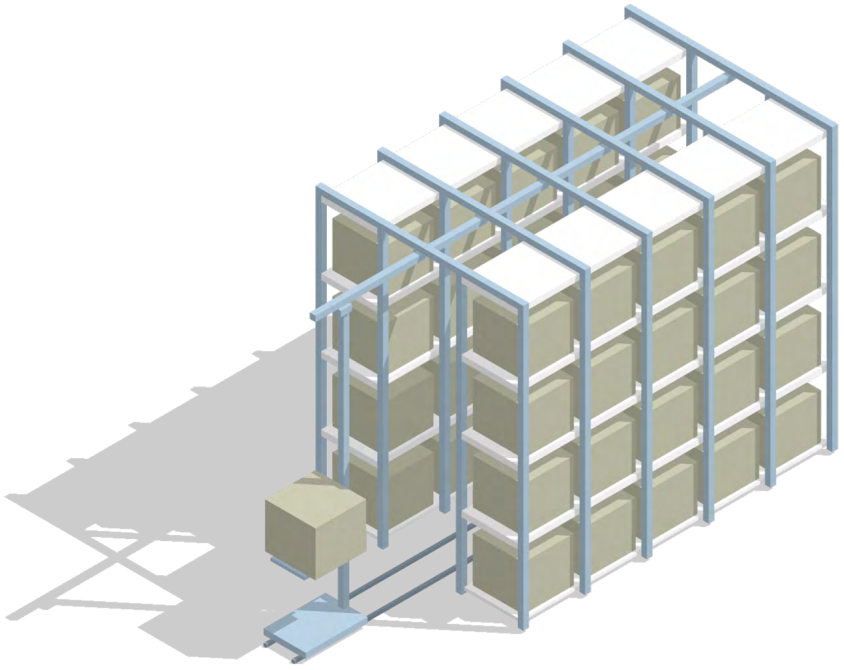


Figure 21:
Storing and Packing

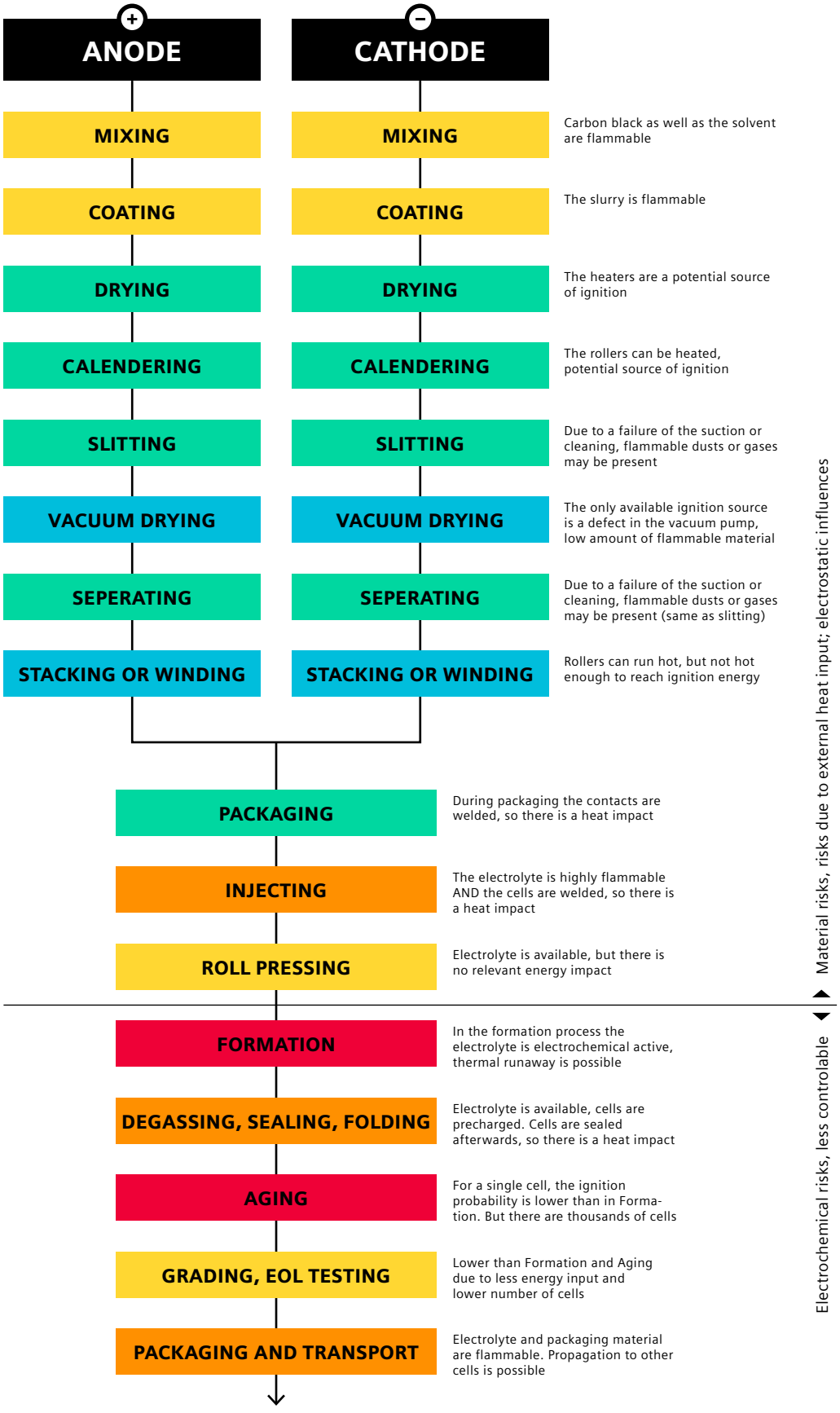
4.3.6.1 Fire Risks and Hazards

Due to the large quantity of stored cells and the existing packing material in this area, the risk is high.

5 Risk Assessment

5.1 Overview

Figure 22:
Overview of the processes and the risks



5.2 Boundaries of the risk assessment

The preliminary risk assessment is based on EN ISO 19353:2019. In this standard, some elements are detailed and shall be part of a fire risk assessment; these elements are transformed into case specific risk drivers in the following list:

- The presence of flammable materials and / or explosive / toxic products
- The likelihood of ignition due to sufficient ignition energy in the production processes and / or electrochemical reactions
- If a fire / explosion / release of toxic gases occurs, it is restricted to a controllable part of the factory or propagated to other parts / cells (thermal runaway)

According to EN ISO 19353:2019 the risk assessment shall be performed using the risk graph shown in Figure 23.

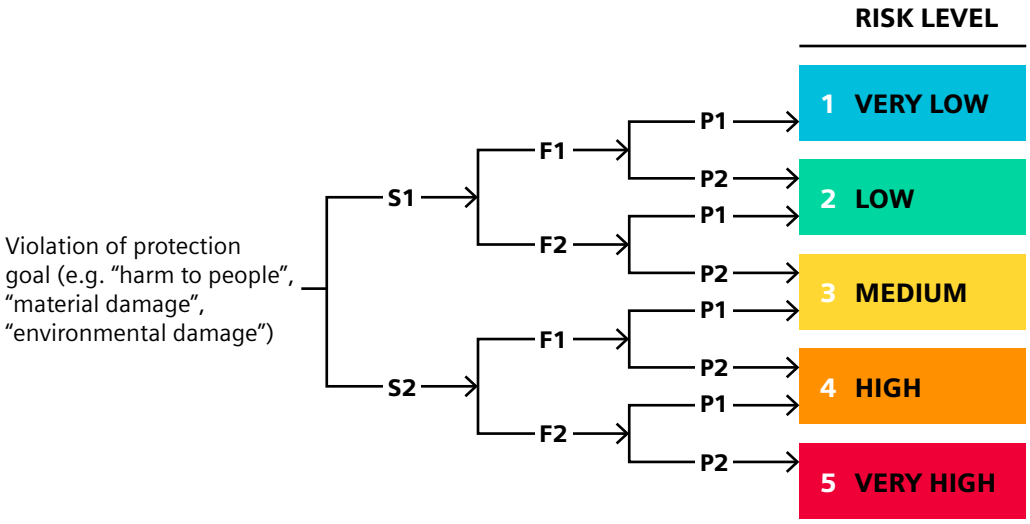


Figure 23:
Risk graph used in EN ISO 19353:2019

In relation to the production of LIB cells, the transferred meaning of the parameters S, F and P is:

S: Flammable Materials (as a benchmark for the extent of damage)
S1: Low extent of damage due to low or no quantity of flammable / explosive / toxic materials present.
S2: High extent of damage due to large quantity of flammable / explosive / toxic materials present or the used materials can be electrochemical active.

F: Production process / Ignition (as a benchmark for the probability)
F1: It is very unlikely or impossible that an ignition can result from production processes (i.e., due to overheating or failure of machines / equipment) and / or electrochemical reactions.
F2: It exists a high probability / frequency of ignition due to production processes (i.e., due to overheating or failure of machines / equipment) and / or electrochemical reactions (i.e., due to internal / external short-circuit, external heat input or mechanical damages).

P: Controllability / Propagation
P1: If fire / explosion / release of toxic gases occurs, it is restricted to a controllable part with no propagation to other parts of the production line.
P2: If fire / explosion / release of toxic gases occurs, it is not restricted to a controllable part with a fast propagation to other parts / cells of the production line (thermal runaway)

Following these parameters, 5 risk categories are identified, which are explained in more detail in the following Table 1 below.

Note: If two explanations / paths in Figure 23 are possible for the same category, the first explanation / path from the top is chosen.

Risk categories

Table 1:
Risk categories with their colour coding

Colour code of the risk categories	Risk assessment
VERY LOW RISK	The risk is **very low**. There is only a low extent of damage due to low or no quantity of flammable / explosive / toxic materials present. It is very unlikely or impossible that an ignition can result from production processes and / or electrochemical reactions. If fire / explosion / release of toxic gases occur it is restricted to a controllable part with no propagation to other parts of the production line.
LOW RISK	The risk is **low**. There is only a low extent of damage due to low or no quantity of flammable / explosive / toxic materials present. It is very unlikely or impossible that an ignition can result from production processes and / or electrochemical reactions. If fire / explosion / release of toxic gases occurs, it's not restricted to a controllable part with a fast propagation to other parts / cells of the production line (thermal runaway).
MEDIUM RISK	The risk is **medium**. There is only a low extent of damage due to low or no quantity of flammable / explosive / toxic materials present. It exists a high probability / frequency of ignition due to production processes and / or electrochemical reactions. If fire / explosion / release of toxic gases occurs, it is not restricted to a controllable part with a fast propagation to other parts / cells of the production line (thermal runaway).
HIGH RISK	The risk is **high**. There is a high extent of damage due to large quantity of flammable / explosive / toxic materials present or the used materials can be electrochemical active. It is very unlikely or impossible that an ignition can result from production processes and / or electrochemical reactions. If fire / explosion / release of toxic gases occurs, it is not restricted to a controllable part with a fast propagation to other parts / cells of the production line (thermal runaway).
VERY HIGH RISK	The risk is **very high**. There is a high extent of damage due to large quantity of flammable / explosive / toxic materials present or the used materials can be electrochemical active. It exists a high probability / frequency of ignition due to production processes and / or electrochemical reactions. If fire / explosion / release of toxic gases occurs, it is not restricted to a controllable part with a fast propagation to other parts / cells of the production line (thermal runaway).

5.3 Risk evaluation

In the following Table 2 the risk evaluation according to Figure 23 is performed. This risk assessment is a generic example. Deviations from the example risk assessment are possible due to changes in the technology used (e.g., machinery equipment, cell chemistry etc.) and the actual conditions on site and shall be adapted on demand.

If specific information is available or if the specific technical implementation differs significantly from the one described in this report a detailed risk assessment using a method described in the IEC 31010:2019 (Risk management — Risk assessment techniques) shall be performed.

Table 2:
Preliminary Risk Assessment
for the production line

#	Process	Flammable Materials (potential extent of damage) S		Production Process / Ignition (potential frequency of occurrence) F		Controllability / Propagation P		Risk
		Description	**Evaluation**	Description	**Evaluation**	Description	**Evaluation**	
1	**Mixing**	Carbon black is one of the materials in the mixture, it is potentially flammable; flammable solvent is also available in a large quantity.	**S2**	Under normal circumstances there exists no ignition source from production process.	**F1**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts of the production line.	**P1**	MEDIUM
2	**Coating**	Mixture (slurry) produced in process No. 1 is flammable and present in a large quantity.	**S2**	Under normal circumstances there exists no ignition source from production process.	**F1**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts of the production line.	**P1**	MEDIUM
3	**Drying**	Coated foils are hardly to ignite; only a low quantity of flammable materials present.	**S1**	There are heaters available and therefore a potential source of ignition due to the production process.	**F2**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts of the production line.	**P1**	LOW
4	**Calendering**	Coated and dry foils have no flammable solvent; no quantity of flammable materials present.	**S1**	Rollers can be heated, high probability / frequency of ignition due to the production process.	**F2**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts of the production line.	**P1**	LOW
5	**Slitting**	Flammable dusts and vapours are present in a low quantity.	**S1**	In normal operation, no ignition due to the production process but a failure of suction is possible.	**F2**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts of the production line.	**P1**	LOW
6	**Vacuum drying**	Low quantity of flammable material present.	**S1**	Fewer potential source of ignition compared with process step No. 3 (Drying), as there are no heaters present.	**F1**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts of the production line.	**P1**	VERY LOW
7	**Separating**	Flammable dusts and vapours are present in a low quantity.	**S1**	In normal operation no ignition due to the production process, but a failure of suction is possible.	**F2**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts of the production line.	**P1**	LOW
8	**Stacking or winding**	Low quantity of flammable material present.	**S1**	Possibly hot rollers, but in normal operation no ignition due to the production process possible.	**F1**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts of the production line.	**P1**	VERY LOW

Table 2:
Preliminary Risk Assessment
for the production line

#	Process	Flammable Materials (potential extent of damage) S		Production Process / Ignition (potential frequency of occurrence) F		Controllability / Propagation P		Risk
		Description	**Evaluation**	Description	**Evaluation**	Description	**Evaluation**	
9	**Packaging**	Low quantity of flammable material present.	**S1**	Contacts are welded, thermal input and therefore a high probability / frequency of ignition due to the production process.	**F2**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts of the production line.	**P1**	LOW
10	**Electrolyte Filling**	Electrolyte is flammable and present in a large quantity.	**S2**	Cells are welded, thermal input and therefore a high probability / frequency of ignition due to the production process.	**F2**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts of the production line.	**P1**	HIGH
11	**Roll pressing (Pouch cells)**	Electrolyte is available and present in a large quantity.	**S2**	No additional source of ignition due to the production process.	**F1**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts of the production line.	**P1**	MEDIUM
12	**Formation**	Electrolyte is available and present in a large quantity. The used materials can be electro-chemically active.	**S2**	Charging process can lead to ignition due to electrochemical reactions.	**F2**	Charging process can lead to thermal runaway with a fast propagation to other parts / cells of the production line.	**P2**	VERY HIGH
13	**Degassing**	Electrolyte is available and present in a large quantity. The used materials can be electro-chemically active.	**S2**	The cell is welded finally, energy input is given and therefore a high probability / frequency of ignition due to the production process.	**F2**	Cell is in a vacuum, low probability of propagation to other parts / cells of the production line.	**P1**	HIGH
14	**Aging**	Electrolyte is available and present in a very large quantity. The used materials can be electrochemically active.	**S2**	Lower state of charge, but thousands of cells with no surveillance and therefore a high probability / frequency of ignition due to electrochemical reactions.	**F2**	Aging process can lead to thermal runaway with a fast propagation to other parts / cells of the production line.	**P2**	VERY HIGH
15	**Grading, EOL Testing**	Electrolyte is available and present in a large quantity. The used materials can be electro-chemically active.	**S2**	Defective cells should have been identified in previous steps and therefore a low probability / frequency of ignition due to electrochemical reactions.	**F1**	Fire / explosion / toxic gas is restricted to a controllable part with no propagation to other parts / cells of the production line.	**P1**	MEDIUM
16	**Storing, Packing (and Transport)**	Electrolyte and flammable packing material are available in a large quantity and can be electrochemically active.	**S2**	Defective cells should have been identified in previous steps and therefore a low probability / frequency of ignition due to electrochemical reactions.	**F1**	Fast propagation to other parts / cells of the production line is possible.	**P2**	HIGH

6 Elements of the fire protection concept development

6.1 Protection goals in the field of fire protection

The mandatory framework (legal and regulatory) forms the basis for the fire safety strategy. This mandatory framework aims at the safety of life and the protection of adjacent property and the environment. Within determining the fire strategy, however, additional safety objectives derived from the overall protection goals shall also be considered (see Ch. 6.2).

Based on the mandatory framework, the outbreak and spread of fire and smoke shall be avoided and the staff safety during escape, rescue and manual firefighting shall be enabled. In order to meet the relevant regulations and co-applicable rules and standards, a fire safety strategy is tailored to the risk profile of the building or plant (e.g., LIB cell production). Deviations from the regulations shall be pointed out within the fire safety strategy. For these deviations it shall be shown that the overall protection goals as well as the detailed objectives, which are being derived from the protection goals, are still being achieved. The fire safety strategy is to be summarized in a fire protection concept.

The fire protection concept describes all basic measures of structural, technical, and organizational fire protection of a building. All measures must be planned and coordinated with each other and their interaction must be ensured.

6.2 Objectives of fire protection

Fire protection is regulated in international, national and municipal regulations, but regardless of all regulations, one should always be clear about the individual protection goal that one wants to achieve for the company.

Fire protection measures shall be selected and combined in such a way that, in their interaction, the required protection objective is ensured cost-effectively and the use and operation of the building can be operated permanently and economically without lowering the safety level. The following basic requirements which are pursued by the legislative, insurance companies and operators should be considered:

The fire protection objectives governed by law are achieved by complying with the following basic requirements:

- Preventing fire outbreak (reduction and separation of fire load and ignition sources, staff instruction, preventive maintenance)
- Preventing spread of smoke and fire (creation of compartments, smoke and heat control systems)
- Enabling short and safe escape routes (proper design in regards of route guidance and width of escape routes, smoke extraction, emergency lighting)
- Early detection and alarming in case of fire (fire detection system)
- Keeping transportation and access routes freely accessible (fire brigade)

The underwriter fire protection objectives are achieved by complying with the following basic requirements:

- Preventing the fire spread (fire walls and fire doors as well as automatic fire extinguishing systems)
- Early and reliable fire detection and alarming (fire alarm system)

The superior corporate goal in fire protection is the limitation of possible damages to ensure the continued existence of the company. The related objectives to be achieved are in detail:

- Limiting the physical damage (object protection, production lines in different rooms)
- Limiting business interruption (attention to bottlenecks, alternative production facility)
- Keeping the data available (fire protection in the IT room, external back up)
- Limiting reputational risk (environmental consequences)

6.3 Fire protection measures and the approach for the LIB cell production

Fire hazards in cell production can be mitigated by a wide variety of measures. Besides typical structural and technical fire protection measures, protective measures can also be taken within machines and processes.

The measures applied for the LIB cell production in the context of this report are divided into following four categories:



Figure 24:
Fire protection categories

The sum of the protective measures represents the holistic protection concept. For each production step (as they are described in Ch. 4), the individual risk (based on Ch. 5) is analysed to identify the best applicable protective measures.

Dependent on the individual risk, the measures do not have to be evenly distributed between the four categories mentioned above; however, the Building Safety will always be implemented as the basic fire protection for each production step.

The four categories and their related measures are described in general as follows:



The Building Safety includes all structural, technical and organizational fire protection measures

- to assume the load-bearing capacity of the construction for a specific period,
- to limit both, the outbreak and spread of fire and smoke within the works and the spread of fire to adjacent construction works and
- to take the safety of the employees and the rescue teams during evacuation and firefighting into consideration.

The Building Safety measures are solely implemented based on the requirements of the building itself, without direct correlation to the different process steps in the first instance.

The exact design of structural and technical fire protection measures depends on the type of building, the dimensions and its use, to name just a few points. Whilst selecting fire protection measures, the local building code as well as the co-applicable rules and standards have to be considered.

For LIB cell production, we assume buildings with floor areas larger than 20.000 m². In accordance with building codes, a large number of structural separation (fire compartments) would be required for such a building size; however, this is often not possible or not desired for system and operational reasons. An increase in size of fire compartments can be realized by means of structural and technical fire protection measures (e.g., in Germany in accordance with the Model Guideline on Structural Fire Protection in Industrial Buildings (MIndBauRL)). Additionally, all components for the structural fire protection shall be designed in accordance with the requirements of EN 13501.

Additional structural fire protection requirements may result from the different process steps.

Taking into account the enormous fire loads of LIB cell production, full-area fire alarm monitoring and equipment with automatic fire extinguishing systems (sprinkler systems) are highly recommended in general as the basic fire protection for the complete LIB cell factory.

With regard to the stability of the building in the event of fire, smoke and heat control systems must be taken into account. The relevant local building regulations and the applicable rules and standards must be applied.

Furthermore, in regards of necessary access and escape routes, applicable local as well as the co-applicable rules and standards have to be considered at the early planning stage.

Due to toxic components in LIB cell production it is necessary to consider extinguishing water retentions during the planning phase. Again, the relevant local building regulations and the applicable rules and standards must be applied.



In Process Safety, the individual process steps are considered in more detail; this consideration may also result in additional structural and technical fire protection measures, taking into account the process related risk based on e.g., the fire load. During detailed planning, separate consideration of the categories of Building Safety and Process Safety with respect to fire protection is not appropriate due to their interdependency. For requirements of the structural fire protection appropriate local codes and standards have to be applied.

In addition to these legal requirements, the production process should be protected so that there is little or no downtime in the event of a fire at the LIB cell production. This is especially essential for economic reasons. Each process step should also be considered in terms of fire protection from the point of view of “availability defined by the company” in order to keep production interruption as low as possible.

In Process Safety, the speed of the measures to be taken is a decisive factor for success. Here, the precise detection of the “off-gas event” with a special fire detector is particularly important and must be taken into account in the process. This fast detection initiates all further measures and is the reason for being so important. Different extinguishing gases can be used for gas extinguishing systems. The most commonly used extinguishing gases are nitrogen, argon and CO2. These extinguishing gases extinguish mainly by lowering the oxygen content to a value at which combustion stops. The necessary reduction depends on the type of extinguishing gas used, the type of object to be extinguished and the material. Oxygen reduction must be achieved within a certain period of time. To ensure the extinguishing effect, oxygen reduction must be maintained for a certain time; however, this is only possible with a air tight enclosure.

Fire protection categories

Building Safety | Process Safety | **Machinery Safety** | Operative Fire Safety

A fire caused by a machine can endanger the entire production site. In the event of a fire, valuable machines and the infrastructure can be severely damaged. Even worse, besides the injury of people, are the considerable economic disadvantages such as downtimes of the machines and the resulting delivery failures. These can cause serious damage to the image or even the loss of customers.

In general, machines should be designed in such way that safety objectives are guaranteed. Consequently, the European Machinery Directive 2006/42/EC is mandatory. For this purpose, a risk assessment of the machine must be carried out, taking into account the specific applicable standards and directives. The potential hazards, including the risk of fire, must be considered in all phases of the machine's life and in all operating modes.

Usually, the risk assessment is carried out according to the standard DIN EN ISO 12100:2010 (Safety of machinery). The aim of the risk assessment is to reduce the risks as far as possible, to identify all hazards that may be posed by the machine, to take appropriate protective measures e.g., fire detection, extinguishing technology and to warn the users of the machine of the remaining residual risks.

Every manufacturer must be aware that risk assessment is required by law and already starts with the process of planning and development.

Fire protection categories

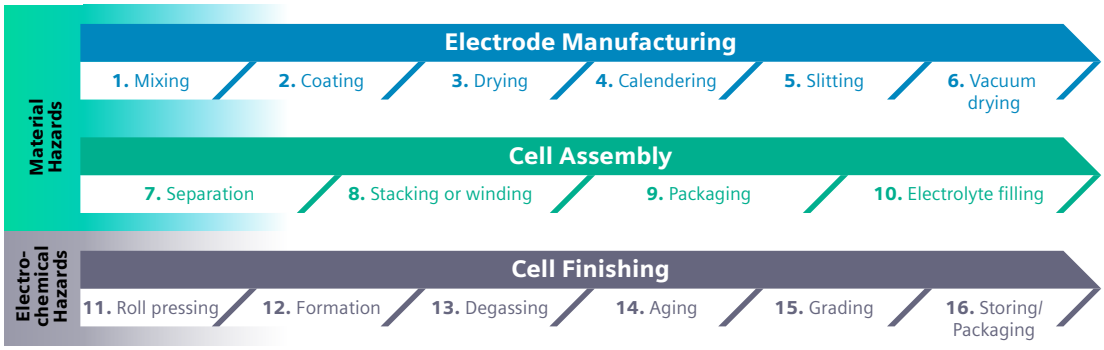
Building Safety | Process Safety | Machinery Safety | **Operative Fire Safety**

The focus here is on organizational measures, for example how to deal with damaged or affected LIB cells. The load carriers or stacking cranes for high bay storage should be considered here and checked for their fire protection behaviour.

6.4 Implementation of specific measures for LIB cell production

Correlation between the fire protection categories and the process steps

« Back to chapter 4



Based on the generic description of the four categories (Building Safety, Process Safety, Machinery Safety and Operative Fire Safety), specific measures of these categories will be applied for each process step in the following according to the respective risk analysed in Ch. 5.

Where additional fire protection measures (structural, technical and / or organizational) are required due to a higher-than-average risk based on the specific production process, adequate measures will be recommended and explained in the following sections.

Process steps No. 1 to 11, No. 13 and No. 15
For the process steps No. 1 to 11, No. 13 and No. 15, besides the basic structural and technical fire protection measures (Building Safety), the additional protective measures are essentially implemented via the machinery itself (e.g., via suitable monitoring, exhaust systems, etc.). The machinery shall be manufactured in such a way that only the materials required for the respective process step are provided. Additionally, the processing takes place within controlled limits and is fully monitored – and finally, the product is immediately fed to the next production step. Effects of these processes remain restricted to a limited area.

Even if the identified process steps vary in the risk between very low and high, as analysed in Ch. 5, the structural and technical measures, e.g., full-area fire alarm monitoring and equipment with automatic fire extinguishing systems, enable the necessary safety. For the process steps No. 1 to 11, No. 13 and No. 15, this means, no additional measures are required to achieve the basic fire protection.

The above approach essentially distinguishes the mentioned process steps from process steps like No. 12, 14 and 16 as the analysed risk, based on Ch. 5, cannot be covered sufficiently by the measures of the Building Safety. Even though the process steps No. 10 and 13 are categorized as “high risk”, they can be protected by the measures of the Building Safety only. For the process step No. 16 – also categorized as “high risk” – additional measures are necessary as the process step itself completely differs from the other “high risk” steps. Thus, special considerations must be made for the process steps No. 12 and 14 (both “very high risk”) as well as for No. 16.

In the following sections, the additional measures besides the ones referring to the minimum Building Safety are described for the process steps No. 12, 14 and 16.

Process step No. 12: Formation incl. Pre-Charging (risk is ranked as very high)
In addition to the cells themselves, the arrangement of the cells (high bay) also contributes to the risk. These following recommended measures, which can be allocated to the four categories (Building Safety, Process Safety, Machinery Safety and Operative Fire Safety) are adapted for the very high-risk process step and represent the most efficient and effective way to offer a high level of safety and availability of an on-going production process.

Following measures should be applied:

Additional measures for Building Safety

The formation process must be separated from other cell production processes and, depending on the floor area of the respective compartment, within the process area because of the enormous fire hazard. As a minimum, fire-resistant walls are recommended for separation and enclosure of the production process. The use of fire-resistant walls for the separation correspond with the requirements of the German model building code for areas of increased fire hazard and with the guideline VDI 3564. Fire walls may also be required for partitioning in some circumstances.

Regarding this production process, analogies can be drawn to Energy Storage Systems (ESS). In accordance to the international standard for ESS, the standard NFPA 855, structural separation of a fire resistance of 120 minutes is required. Even if the fire resistance rating based on US-American codes and standards cannot be compared directly with the one of German or European codes and standards due to different test procedures for analysing the fire resistance rating of structural components or building products, the value of 120 minutes represents a helpful point of reference.

The FM-Global Data Sheet 5-33, another standard for ESS, specified minimum separation distances from non-combustible construction elements and between the aisle faces of adjacent racks of 1.8 m (6 ft).

In general, as part of the structural safety, the limitation of the quantity of hazardous materials and / or equipment shall be considered and reduced wherever possible.

It is recommended to connect the fire detection systems with an automatic fire extinguishing (e.g., gas extinguishing) and suppression system. An appropriate suppression system for the formation process is a sprinkler system (water fire suppression system). These fire suppression systems can be allocated to Process and / or Machinery Safety. Therefore, they are no longer seen as additional measures under Building Safety.

Process Safety

The decisive point in Process Safety is the early and precise detection of the off-gas event with a special fire detector. The signal arriving in the fire detection system is forwarded once to the PLC control for shutdown of the formation process and typically used for immediate activation of the nitrogen extinguishing system. The discharge of the extinguishing agent prevents the formation of an explosive atmosphere. Attention must be paid to the tightness of the formation box as well as the air flow within the formation tower - these two requirements are necessary prerequisites for an effective gas extinguishing system.

Machinery Safety

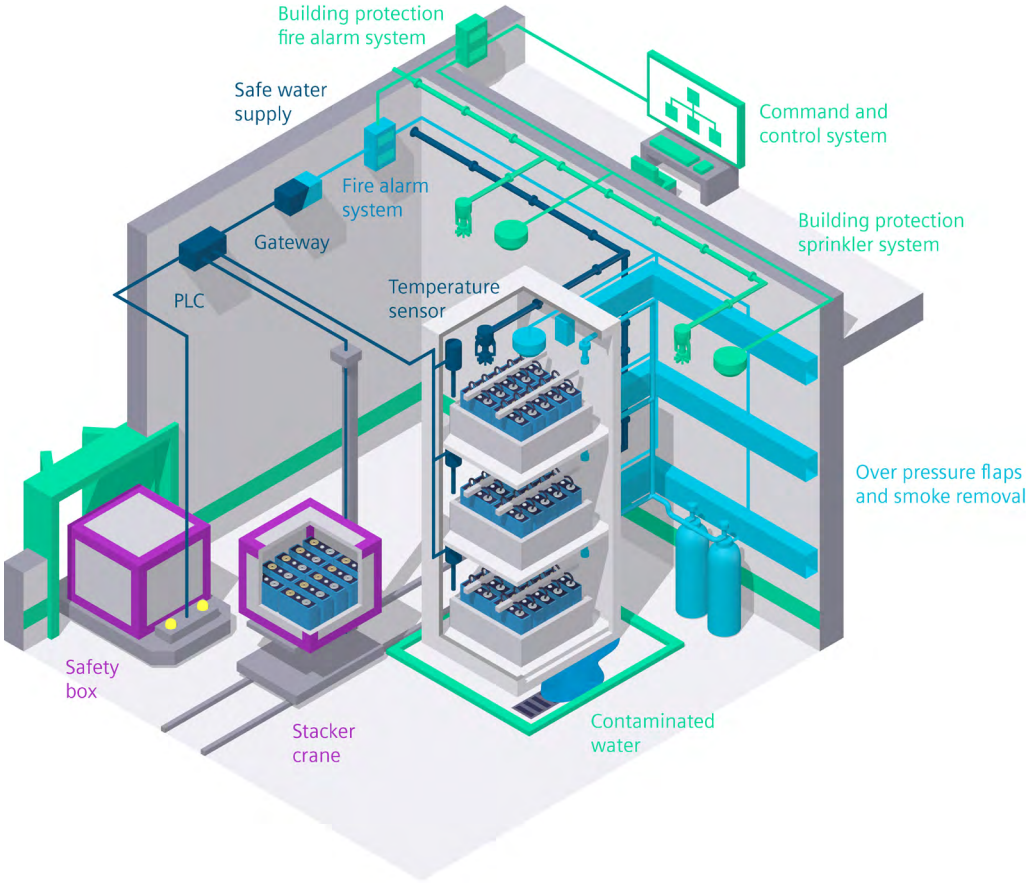
To ensure that the requirements of the Machinery Directive are met even if the gas extinguishing system is ineffective, a temperature-controlled water extinguishing system must be provided for the high bay storage. However, this should only ever be the last of all measures to avoid any damages to the machine caused by extinguishing water.

It is recommended to connect the fire detection systems with an automatic fire extinguishing system. While reducing or displacing oxygen, gas extinguishing systems are a very effective measure.

Operative Fire Safety

To ensure the protection of all employees and the environment, the safe handling of affected LIB cells must be regulated. If possible, the affected LIB cells are to be picked using a stacking crane and removed from the affected area and disposed of properly. By automating this process, risks of personal injuries can be pared down to a minimum.

Figure 25:
Protected Formation Process



- Building Safety
- Process Safety
- Machinery Safety
- Operative Fire Safety

Process step No. 14: Aging (risk is ranked as very high)

These following recommended measures, which can be allocated to the four categories (Building Safety, Process Safety, Machinery Safety and Operative Fire Safety) are adapted for the very high-risk process step and represent the most efficient and effective way to offer a high level of safety and availability of an on-going production process.

Following measures should be applied:

→ **Additional measures for Building Safety**

The aging process must be separated from other cell production processes and, depending on the floor area of the respective compartment, within the process area because of the enormous fire hazard. As a minimum, fire-resistant walls are recommended for separation and enclosure of the production process. The use of fire-resistant walls for the separation correspond with the requirements of the German model building code for areas of increased fire hazard and with the guideline VDI 3564. Fire walls may also be required for partitioning in some circumstances.

The following guidelines should only be seen as reference as, during the aging process, no further charging will take place; nevertheless, the process itself with heating and cooling of the LIB cells and without monitoring via PLC contains a very high risk. These following guidelines can be applied as recommendation.

Regarding this production process, analogies can be drawn to Energy Storage Systems (ESS) – similar to the process step No. 12. In accordance to the international standard for ESS, the standard NFPA 855, structural separation of a fire resistance of 120 minutes are required. The value of 120 minutes represents a helpful point of reference even if the fire resistance rating based on US-American codes and standards cannot be compared directly with the one of German or European codes and standards.

The FM-Global Data Sheet 5-33, another standard for ESS, specified minimum separation distances from non-combustible construction elements and between the aisle faces of adjacent racks of 1.8 m (6 ft).

In general, as part of the structural safety, the limitation of the quantity of hazardous materials and / or equipment shall be considered and reduced wherever possible.

The area of the Aging must be considered and designed like a high rack warehouse in the fire protection assessment. For limiting any possible fire propagation as a result of a thermal runaway e.g., due to defective LIB cells the installation of an automatic fire suppression is recommended. An appropriate suppression system for the formation process is a sprinkler system; therefore, besides having a ceiling protection, it is necessary that each rack is equipped with sprinkler nozzles. For the dimension of the sprinkler system the standard NFPA 855 and the technical rule VdS CEA 4001 should be considered.

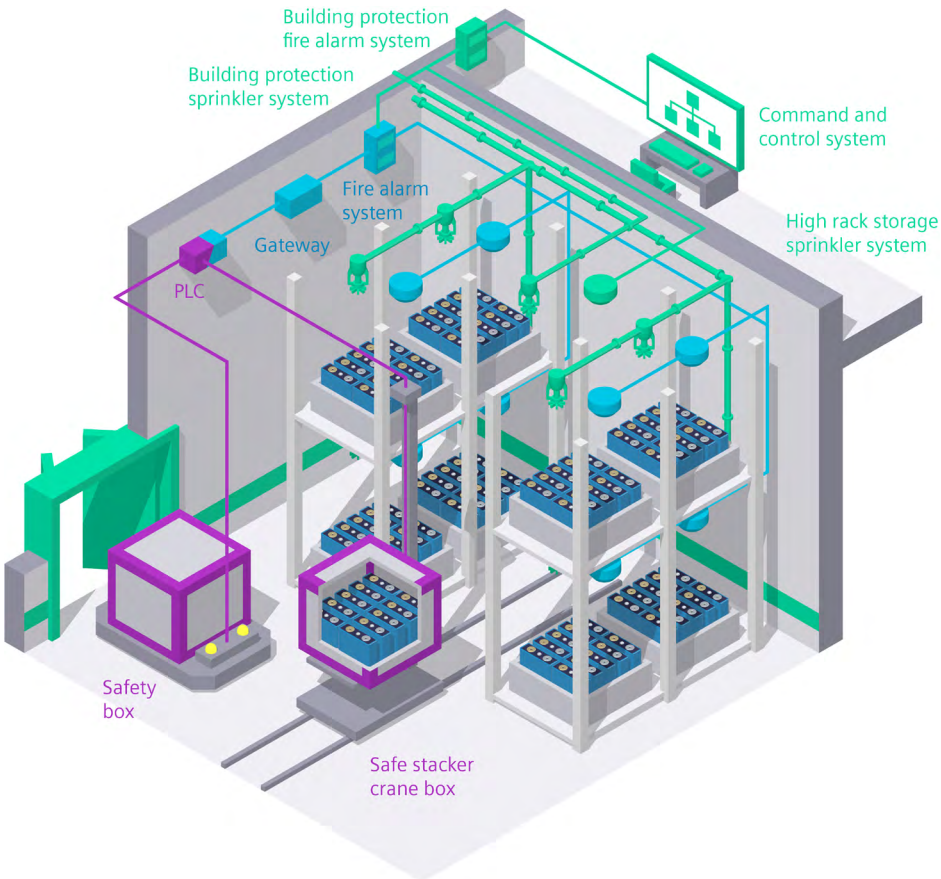
Process Safety

The decisive point in Process Safety is the early and precise detection of the off-gas event of the affected LIB cell with a suitable fire detector. The exact positioning of the individual fire detectors within the aging rack must be ensured. The signal arriving in the fire alarm system is forwarded to the PLC control for activating the stacker crane.

Operative Fire Safety

To ensure the protection of all employees and the environment, the safe handling of affected LIB cells must be regulated. If possible, the affected LIB cells must be picked and removed from the affected area using a stacker crane and disposed of properly to a designated area. This procedure must be carried out quickly after detection to avoid deformation of the trays in the rack, which would then make removal impossible. From a fire safety point of view, it is recommended to use metal trays and not plastic trays. By automating this process, risks of personal injuries can be pared down to a minimum.

Figure 26:
Protected Aging Process



- Building Safety
- Process Safety
- Machinery Safety
- Operative Fire Safety

Process step No. 16: Storing, Packing (and Transport) (risk is ranked as high)
These following recommended measures, which can be allocated to the four categories (Building Safety, Process Safety, Machinery Safety and Operative Fire Safety) are adapted for the high-risk process step and represent the most efficient and effective way to offer a high level of safety and availability of an on-going production process.

Following measures should be applied:

Additional measures for Building Safety

The high bay warehouse must be separated from other cell production processes and, depending on the floor area of the respective compartment, within the process area because of the enormous fire hazard. As a minimum, fire-resistant walls are recommended for separation and enclosure of the production process. The use of fire-resistant walls for the separation correspond with the requirements of the German model building code for areas of increased fire hazard and with the guideline VDI 3564. Fire walls may also be required for partitioning in some circumstances.

The following guidelines should only be seen as reference as no further charging will take place. In addition to cells themselves, packaging materials represent further fire loads. Thus, the requirements of these guidelines can be applied as recommendation.

Regarding this production process, analogies can be drawn to Energy Storage Systems (ESS) – similar to the process steps No. 12 and 14. In accordance to the international standard for ESS, the standard NFPA 855, structural separation of a fire resistance of 120 minutes are required. The value of 120 minutes represents a helpful point of reference even if the fire resistance rating based on US-American codes and standards cannot be compared directly with the one of German or European codes and standards.

The FM-Global Data Sheet 5-33, another standard for ESS, specified minimum separation distances from non-combustible construction elements and between the aisle faces of adjacent racks of 1.8 m (6 ft).

For limiting any possible rapid propagation of fire or toxic gases as a result of a thermal runaway of LIB cells within the high bay warehouse, the installation of an automatic fire suppression is recommended. An appropriate suppression system is a sprinkler system. Therefore, besides having a ceiling protection, it is necessary that each rack of the high bay warehouse is equipped with sprinkler nozzles. For the dimension of the sprinkler system the standard NFPA 855 and the technical rule VdS CEA 4001 should be considered.

7 References

[L1] *PEM of RWTH Aachen University and VDMA (2018): Lithium-ion battery cell production process, 3rd Edition. Frankfurt am Main: PEM of RWTH Aachen University and VDMA (2018)*

[L2] *Technische Universität Braunschweig – iPAT Institut für Partikeltechnik: Mischen und Dispergieren – Bereich: Batterieverfahrenstechnik.*

[L3] *TIMCAL Graphite & Carbon – Ensaco 150/210/250/260/350 granular, Ensaco 150/250P, Super P, Super P-Li, C-NERGY SUPER C 45/65 – Material Safety Data Sheet, version 2.1.1 (2012)*

[L4] *Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA: Elektrodenbeschichtung.*

[L5] *ProZell Kompetenzcluster zur Batteriezellproduktion: Erhöhung der Durchsatzgeschwindigkeit in der Elektrodenproduktion durch ein innovatives Trocknungsmanagement (Epic).*

[L6] *Lithium-Ionen-Batterietechnik – Ein Einblick in die Lithium-Ionen-Batterietechnik: 6. Herstellung und Prozessabläufe.*

[L7] *Bundesministerium für Bildung und Forschung – werkstofftechnologien.de: Batterieforschung.*

[L8] *Fraunhofer-Institut für Techno- und Wirtschaftsmathematik ITWM: Prozesse in der Produktion von Lithium-Ionen-Batterien simulieren.*

[L9] Kampker, A. (2014): Elektromobilproduktion. Heidelberg: Springer Vieweg (2014)

[L10] *LTS Research Laboratories, Inc. – Lithium Hexafluorophosphate – Safety Data Sheet.*

[L11] *Carl Roth – Lithiumfluorid ROTI®METIC 99,99 % (4N) – Sicherheitsdatenblatt, Version 2.0 de (2018)*

[L12] *Breckland Scientific – Phosphorus Pentachloride – Safety Data Sheet (2018)*

[L13] *Keil, P. (2017): Aging of Lithium-Ion Batteries in Electric Vehicles – Dissertation at TUM Department of Electrical and Computer Engineering, Technical University of Munich. Munich: Institute for Electrical Energy Storage Technology, TUM (2017)*

[L14] *The 27th International Electric Vehicle Symposium & Exhibition (2013) – Lithium-ion battery aging: Representative EV cycling profiles compared to calendar life, lecture by Grolleau, S., Delaille, A., Gualous, H. (2013)*

[L15] *IOP Conference Series: Materials Science and Engineering (2019) – Grading of Lithium Ion Battery Module for Public street lighting, paper by Kartini, E., Sudaryanto, S., Honggowiranto, W., Sudjatno, A., Fadjri, A., Marto, I., Rofika, R.N.S. (2019)*