The STABALID Project: Risk Analysis of Stationary Li-Ion Batteries for Power System Applications

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Abstract

This work presents a risk analysis performed to stationary Li-ion batteries within the framework of the STABALID project. The risk analysis had as main objective analysing the variety of hazards and dangerous situations that might be experienced by the battery during its life cycle and providing useful information on how to prevent or manage those undesired events. The first task of the risk analysis was the identification of all the hazards (or risks) that may arise during the battery life cycle. Afterwards, the hazards identified were mapped in the different stages of the battery life cycle and two analyses were performed for each stage: an internal problem analysis and an external peril analysis. For both, the dangerous phenomena and the undesirable events resulting from each hazard was evaluated in terms of probability of occurrence and severity. Then, a risk assessment was carried out according to a predefined risk matrix and a preliminary set of risk mitigation measures were proposed to reduce their probability of occurrence and/or their severity level. The results obtained show that it is possible to reduce the probability of occurrence/severity of all the risks associated to the battery life cycle to acceptable or tolerable levels.

Keywords: Risk analysis; Risk evaluation; Risk mitigation measures; STABALID project; Stationary Li-ion batteries.

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1. Introduction

Renewable Energies Sources (RES), especially through the Kyoto protocol, [1], and the European Union's 20% renewable penetration goal by 2020, [2], are gradually increasing their share in the total energy consumption, [3]. These events, in addition to the growing need to reduce countries' fossil fuels dependency, is leading policy makers to implement measures to diversify their energy mixes, by seeking alternative forms to generate energy. Therefore, a more efficient use of the endogenous renewable energy sources available is desirable. However, the intermittent characteristic of some renewable resources, especially wind, [4], and the fact of a large number of renewable generation units not being capable of providing ancillary services are two reasons that are slowing down the large scale integration of RES.

In order to overcome these problems, technical solutions that enable the management of the energy produced by RES should be considered and implemented. Among the possible solutions, large stationary batteries installed at strategic points of the electricity network can be potential solutions that allow a larger integration of RES while keeping the power systems stability and quality of service levels unchanged and, at the same time, reducing the renewable energy wasted, [5-7].

From all the technologies of large stationary batteries, Lithium-ion (Li-ion) technology is considered as one of the best solutions due to its intrinsic characteristics, providing an adequate energy-to-power ratio to be used in combination with the various types of RES, [8,9]. However, the lack of experience by the end-users, especially for large scale integration levels, raises a number of questions related with the safety and performance of the stationary batteries at the scale considered, [10,11].

Smaller Li-ion batteries are already being used for other purposes, such as cell phones and portable computers, what led to the definition of several standards, [12-16]. The emerging interest on hybrid and electric vehicles also contributed to the definition of several other

standards, [17-19]. Since in the industrial framework, the deployment of large Li-ion batteries is just at an initial stage, presently there are no available standards for this specific field of application. Considering this conjecture and to regulate safety issues and increase market acceptability a specific standard focused on safety testing for stationary Li-ion batteries is necessary.

The STABALID (STAtionary Batteries LI-ion safe Deployment) project intends to deliver a proposal for a new standard, defining the most appropriated testing methodology for stationary Li-ion batteries, [20]. This testing methodology should have as basis a thorough risk analysis procedure. This paper presents the risk analysis that was performed in the first task of STABALID, which started with a review of the state of the art regarding the design characteristics of the Li-ion batteries selected for evaluation (*Intensium® Max* developed by SAFT Batteries, [21]), the specificity of the stationary batteries and the previous experience of Li-ion batteries manufacturers and users. Secondly, the risks associated with the production, storage, transportation, installation, operation, periodic inspections, maintenance, decommissioning and removal of stationary Li-ion batteries were identified, characterised and evaluated. Afterwards, a risk evaluation was performed to assess the severity and probability of occurrence of the hazards previously identified. Based on the results obtained, a set of potential solutions to mitigate the risks was proposed and evaluated. The outcomes of the analysis performed provide valuable information, which should be considered in the future development of the safety testing methodologies to be proposed in the new standard.

2. Risk Analysis of Stationary Li-Ion Batteries

Regardless of the size, the safety of Li-ion batteries is intrinsically related with the safety at the cell level. Several phenomena can occur at cell level, such as chemical imbalance or internal short-circuit, resulting in failures. Li-ion battery failures may also be caused by external sources such as exposure to external heating, mechanical damages, electrical abuse

conditions or by internal sources resulting from manufacturing problems or defects.

The potential risks can be defined as an external or internal event that can potentially result in a threatening condition or malfunction for the equipment, system or surrounding environment. In order to mitigate these risks, several safety tests and standards on Li-ion batteries have already been developed. However, the majority of them only consider small or medium size applications, such as consumer electronics or automotive applications [22].

Due to their size and complex structure, large scale stationary batteries can be exposed to extreme conditions during their life cycle, which are considerably different from small dimension applications such as cell phones. These specificities were taken into account in the risk analysis performed in this work, which is composed of 4 stages:

- **Risk Identification** → Identification of the risks that may appear in each stage of the battery life cycle;
- **Risk Evaluation** → Qualitative evaluation of the risks that may appear in each stage of the battery life cycle;
- **Recommended Mitigation Measures** → Safety measures recommended to mitigate the risks identified;
- **Risk Re-evaluation** → Qualitative evaluation of the risks that may appear in each stage of the battery life cycle, assuming that the recommended mitigation measures were implemented.

The methodology followed in these 4 stages is described in the following section.

3. Methodology

3.1 Risk Identification

The first stage of the risk analysis is the identification of all the hazards (or risks) that may arise during the life cycle of the battery. The identification of the hazards was performed taking into account the results obtained from surveys made to the STABALID Project

partners, literature reviews and a workshop where the expertise of specialized staff of SAFT Batteries, INERIS, TÜV SÜD and EDP Distribuição was collected. After analysing all the hazards (green shapes), they were separated into seven main categories (red shapes), as listed in Figure 1.

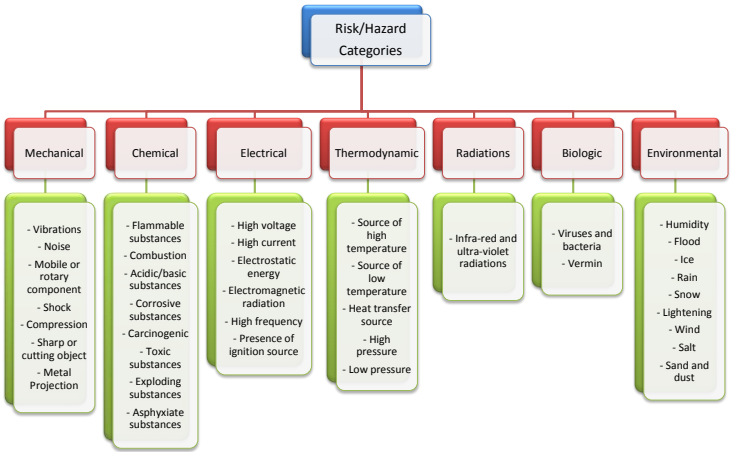

Figure 1 – Risks/Hazards considered divided by categories

3.2 Risk Evaluation

The second stage was the identification of the different phases of the battery life cycle, which were considered in the risk analysis. The stages considered are presented in Figure 2. For the purpose of this work, the risks of the transportation and removal stages were considered to be the same, since the removal of the battery was considered to be the act of taking it away from the site where it was operating to somewhere else. The risks of the installation/decommissioning and periodic inspection/maintenance were also considered to be the same, since these are very similar activities.

Afterwards, the hazards previously identified (Figure 1) were mapped in the different stages of the battery life cycle (Figure 2). The same hazard may appear in different stages of the battery life cycle. The results of this mapping process, for each stage, are presented in Table 1.

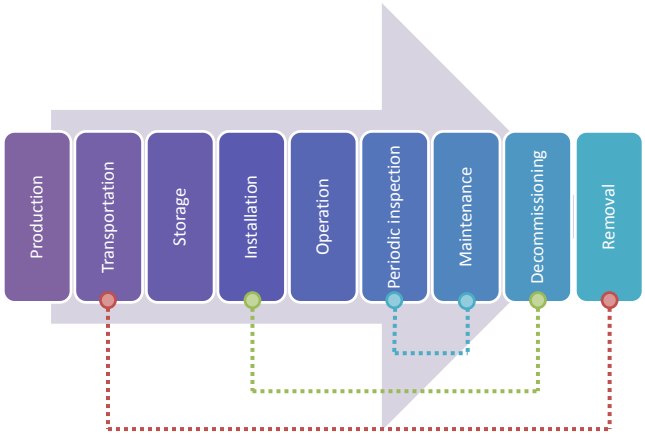

Figure 2 – Stages of the battery life cycle considered

Production	Storage		Transportation/Removal		Installation/Decommissioning		Operation		Maintenance/Inspections	
Internal Problem Analysis	**Internal Problem Analysis**	**External Peril Analysis**	**Internal Problem Analysis**	**External Peril Analysis**	**Internal Problem Analysis**	**External Peril Analysis**	**Internal Problem Analysis**	**External Peril Analysis**	**Internal Problem Analysis**	**External Peril Analysis**
Weakened cell structure	Sharp or cutting objects	Vibrations	Flammable substances	Vibrations	Sharp or cutting objects	Vibrations	Mobile or rotary component	Vibrations	Mobile or rotary component	Shock
Overall production quality	Flammable substances	Shock	Acidic or corrosive substances	Shock	Flammable substances	Shock	Sharp or cutting objects	Shock	Sharp or cutting objects	Sharp or cutting objects
Bad assembly	Acidic or corrosive substances	Sharp or cutting objects	High temperature or heat transfer source	Stress, compression	Acidic or corrosive substances	Sharp or cutting objects	Flammable substances	Sharp or cutting objects	Flammable substances	Metal projection
Bad conception regarding constructive aspects	Carcinogenic substances	Metal projection	High pressure	Sharp or cutting objects	Carcinogenic substances	Metal projection	Acidic or corrosive substances	Metal projection	Acidic or corrosive substances	Electrostatic energy
	Toxic substances	High voltage (>120V)		Metal projection	Toxic substances	Electrostatic energy	Carcinogenic substances	High voltage	Carcinogenic substances	High temperature
	Asphyxiating substances	High current		Electrostatic energy	Asphyxiating substances	High temperature	Toxic substances	High current	Toxic substances	Vermin and other animals
	High voltage (>120V)	Electrostatic energy		High temperature or heat transfer source	High voltage (>120V)	Vermin and other animals	Asphyxiating substances	Electromagnetic radiation	Asphyxiating substances	Humidity, condensation
	High current	High temperature		Humidity, condensation	High current	Humidity, condensation	High voltage (>120V)	Electrostatic energy	High voltage (>120V)	Rain
	High temperature	Vermin and other animals		Rain	High temperature	Rain	High current	High temperature or heat transfer source	High current	Sand and Dust
	High pressure	Humidity, condensation		Salt	High pressure	Sand and Dust	High temperature or heat transfer source	Vermin and other animals	High temperature or heat transfer source	
		Flood		Sand and Dust			High pressure	Humidity, condensation	High pressure	
		Rain					Overheat	Flood		
		Salt					Internal short circuit	Rain		
		Sand and Dust					Over charge	Lightning		
							Recharge of an over discharged cell	Salt		
							Loss of cell tightness	Sand and Dust		
							External short circuit			
							Fire			

Table 1 – Mapping of the hazards in the stages of the battery life cycle

As it can be inferred from Table 1, two distinct analyses were made for each stage of the battery life cycle:

1. **Internal problem analysis** → This analysis is focused on battery internal problems and/or components failure that may result in an aggression over the surrounding environment (people and/or equipment in the battery vicinity);

2. **External peril analysis** → This analysis is focused on the external aggressions from the surrounding environment that may cause some battery components failure. The battery components failure, by its turn, may also result in an aggression over the surrounding environment (people and/or equipment in the battery vicinity).

The main characteristics and the role of the battery and of the environment in both analyses are schematically presented in Figure 3.

The following step was to describe and characterise in detail the hazards identified for each stage of the battery life cycle (Table 1). To this end, additional information was collected and used to better describe each of the hazards previously identified, as shown in the tables presented in section 6.

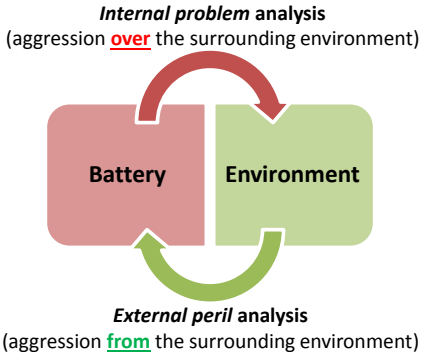

Figure 3 – Analyses performed for each of the stages of the battery life cycle

It should be noted that in this work, namely in the first column of the tables presented in section 6, the word ***Hazard*** is used to define ***something that is dangerous and likely to cause any kind of damage***. The remaining columns of the tables include the additional information used to describe the hazard. It should be noted that the name attributed to each of the columns should be interpreted taking into account the type of analyses made in the table: internal problem analysis or external peril analysis. For better comprehension of the tables, and to avoid any misunderstandings that the names attributed to the columns may cause, the following definitions should be taken into account:

- **Element** *(internal problem analysis)* → Part of the battery that may cause damage;

- **Element** *(external peril analysis)* → Part of the battery exposed to the hazard that is likely to be damaged;
- **Cause** *(internal problem analysis)* → Origin of the failure that may cause damage to people and equipment in the battery surroundings;
- **Cause** *(external peril analysis)* → Origin of the failure that may cause damage to the battery element;
- **Dangerous occurrence** → Occurrence (something that happens) that may lead to an undesirable event (*e.g.* battery or module fire);
- **Dangerous situation** → The set of circumstances in the battery surroundings that may lead to an undesirable event (*e.g.* people or equipment in proximity);
- **Undesirable event** → The result of a dangerous occurrence and a dangerous situation (*e.g.* burnt or fire propagation);
- **P (Probability level)** → Probability level of undesirable event occurrence;
- **S (Severity level)** → Severity level of the undesirable event;
- **RA (Risk Assessment)** → Risk assessment of the undesirable event;
- **RMM (Risk Mitigation Measures)** → Safety measures proposed to reduce the risk level;
- **PRMM (New probability level)** → Probability level of undesirable event occurrence after the implementation of the safety measures recommended;
- **SRMM (New severity level)** → Severity level of the undesirable event after the implementation of the safety measures recommended;
- **RARMM (New risk assessment)** → Risk assessment of the undesirable event after the implementation of the safety measures recommended.

In order to clearly understand the elements considered during the risk identification, the following terms are used:

- **Cell** → Refers to the Li-ion unit that provides a source of electrical energy by direct conversion of chemical energy;
- **Module** → Compact module that integrates several Li-ion cells;
- **Array of Modules** → Composed of several modules in series, including their management system;
- **Electronic Boards** → Refers to the electronic boards implemented in the battery system;
- **Battery System** → Refers to the components inside the battery container (cells, modules, electronic boards, cables, etc.);
- **Container** → Refers to the metallic structure surrounding the "Battery System";
- **Fire Suppression System** → Fire prevention system placed inside the battery container;
- **Air Conditioning System** → Active cooling system placed inside the battery container.

The intervals for **P** (probability level of the undesirable event occurrence) and **S** (severity level of the undesirable event), included in the tables presented in section 6, were defined after a detailed analysis of the data made available by the STABALID project partners. It should be noted that the definition of the probability and severity levels was made taking into consideration the expertise of specialized staff of SAFT Batteries, INERIS, TÜV SÜD and EDP Distribuição. The probability and severity levels considered in the risk analysis are presented in Table 2 and Table 3, respectively.

Level	Probability
1	$P \leq 10^{-9} / h \rightarrow$ Improbable Event
2	$10^{-9} < P \leq 10^{-7} / h \rightarrow$ Remote Event
3	$10^{-7} < P \leq 10^{-5} / h \rightarrow$ Occasional Event
4	$P > 10^{-5} / h \rightarrow$ Probable Event

Table 2 – Probability levels (P)

Level	Severity	Description
1	Minor	• Slight degradation of battery performance → the owner can still use the battery • Maintenance operation is advisable, but not mandatory → limited cost impact • Low risk for user or operator → small reduction in safety conditions
2	Major	• Considerable degradation of battery performance → the owner can still use the battery but a quick maintenance is requested • Low risk for user or operator → important reduction in safety conditions
3	Hazardous	• The battery is out-of-service → possibility of significant damage on the battery • Immediate maintenance is mandatory → significant intervention cost • Low risk for user or operator (possible injury) → large reduction in safety conditions
4	Catastrophic	• The battery is out-of-service → major damage on the battery • Significant risk for user or operator (significant or fatal injury) or important environmental degradation

Table 3 – Severity levels (S)

The **RA** (Risk Assessment of a given undesirable event) was computed afterwards, taking into account the **P** and **S** levels attributed previously to the undesirable event under analysis. For this purpose, a two-input data table was used (Table 4), where the inputs are precisely **P** and **S**. Depending on the **P** and **S** levels attributed, an undesirable event can be classified as *Acceptable*, *Tolerable* or *Intolerable*.

RA		S			
		1	2	3	4
P	1	Acceptable	Acceptable	Acceptable	Tolerable
	2	Acceptable	Acceptable	Tolerable	Intolerable
	3	Acceptable	Tolerable	Intolerable	Intolerable
	4	Tolerable	Intolerable	Intolerable	Intolerable

Table 4 – Risk assessment based on the P and S levels

3.3 Recommended Mitigation Measures and Risk Re-evaluation

After completing the risk assessment, adequate **RMM** (risk mitigation measures) were proposed in order to reduce the probability and/or severity levels of all the risks, no matter their classification (*Acceptable*, *Tolerable* or *Intolerable*). Nevertheless, particular attention was given to the risks classified as *Tolerable* and *Intolerable*, given that the main purpose of this task was propose risk mitigation measures that, if implemented, would allow classifying all the risks as *Acceptable*. All the **RMM** proposed are described in section 7 (Table 16).

After defining the most adequate **RMM**, a new probability and severity level ($\mathbf{P_{RMM}}$ and $\mathbf{S_{RMM}}$, respectively) was attributed to the undesirable events, according to the definitions presented in Table 2 and Table 3.

The $\mathbf{RA_{RMM}}$ (new risk assessment) was computed afterwards, taking into account the $\mathbf{P_{RMM}}$

and $\mathbf{S_{RMM}}$ levels attributed previously to the undesirable event under analysis. Depending on the $\mathbf{P_{RMM}}$ and $\mathbf{S_{RMM}}$ levels attributed, the undesirable events are again classified as *Acceptable*, *Tolerable* or *Intolerable*.

It should be referred that this latter procedure was iteratively repeated until all the undesirable events were classified as *Tolerable*.

In order to provide a clear overview of the methodology described above, a diagram with all the steps followed in the risk analysis is presented in Figure 4.

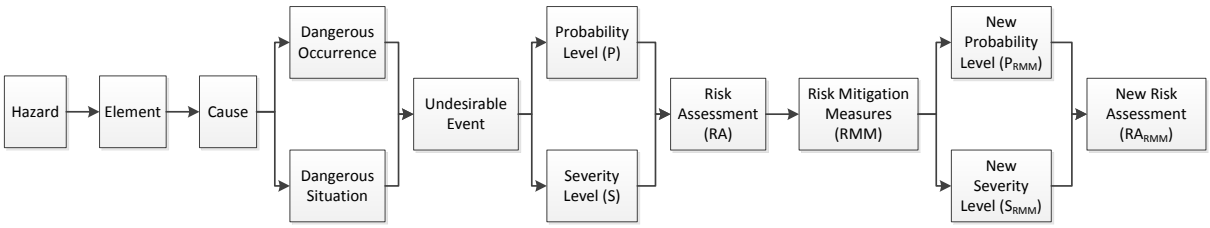

Figure 4 – Diagram of the risk analysis methodology

As previously referred, all the information collected and results obtained from the implementation of the risk analysis methodology were processed and compiled into the set of tables presented in section 6.

4. Results Analysis

4.1 Production Stage

Li-ion batteries are slowly becoming a more significant and important technology regarding energy storage solutions. In this context, adequate safety performances in addition to an extended life cycle are key factors that should be taken into account by the manufacturers. An appropriate design and manufacturing process of the cells/modules and their incorporation into a flexible storage systems that can be rapidly deployed in the grid are essential to meet customer's exact power and energy requirements. Failures during assembling, due to technical or human nature, can damage or influence the future performance of the battery.

At the assembly line, visible and detectable defects, such as drop or physically damaged modules are immediately replaced. Still, there are a number of possible defects during cell

production that may escape this visual inspection such as contaminants introduction, electrode defects, components misalignment or welding defects. To deal and mitigate these defects a number of manufacturing quality control techniques are normally applied and also the manufacturer carries out reliability tests (such as charge/discharge cycles, resistance measurements or X-ray) to ensure that the equipment is distributed without damage or defects. However there is still a risk (even low) that a very subtle defect is not detected.

The main risk related with production is cell contamination or defect. The potential causes can be assigned to human or technical failure during assembling, incorrect dimensioning or lack of safety elements. Even though the batteries may succeed in the trials conducted by the manufacturer, the safety tests performed may not simulate all the conditions that batteries may experience when integrated in the electricity grid, where the combination of events can produce unpredicted reactions. For instance, the lack of safety elements can only result in failure when severe extreme overcurrent events occur during operation, therefore undetectable when small scale tests are performed for the individual battery modules.

Table 5 of section 6 presents all the information collected and results obtained from the risk analysis performed for the internal problem analysis. The external peril analysis was not performed for the production stage, since in this phase the battery surrounding environment is carefully controlled and the risk of occurring an undesirable event due to an external aggression is negligible.

4.2 Transportation/Removal

Transportation and removal should be neutral stages for the Li-ion batteries, in the sense that transportation/removal means moving the battery from the factory to the location where it is going to be installed and from here to somewhere else. These stages should be carried out by trained personnel with the adequate equipment in order to maintain the original characteristics of the batteries. Safety regulations and supervision during these phases are essential

procedures to maintain the safety conditions. The most common procedures for moving the battery container are road and sea transportation. The latter is more used in long travels.

Table 6 and Table 7 of section 6 present the information collected and results obtained from the risk analysis performed for the internal problem analysis and the external peril analysis.

4.3 Installation/Decommissioning

It is very important to collect information and specifications from the manufacturer so that the batteries selected can meet the required performance without unexpected reactions or limitations. At this point, the batteries characteristics must meet, without reservations, the customer requirements since the installation stage precedes the operational phase where it is expected that the selected storage solution will attend its purpose. Correct connections, proper protections, sustained by technical supervision should be the main concerns at the installation stage, as well as at the decommissioning, since this is basically the opposite of the installation.

Table 8 and Table 9 of section 6 present the information collected and results obtained from the risk analysis performed for the internal problem analysis and the external peril analysis.

4.4 Storage

The storage of the battery, as considered in the risk analysis, is the act of keeping the battery in a specific place for use in the future. Thus, the storage phase occurs at different times of the battery life cycle. The battery can be stored on the manufacturer site waiting to be transported by road or ship, on the harbour waiting to be boarded on a ship or on the client site, waiting to be installed and put in operation. The storage sites should be safe places with restricted access to reduce the probability of shock or other external aggression occurrence. It is also important to assure that during the storage phase the temperature of the environment external to the battery system and modules is lower than the maximum recommended by the manufacturer.

Table 10 and Table 11 of section 6 present all the information collected and results obtained from the risk analysis performed for the internal problem analysis and the external peril

analysis.

4.5 Operation

Large stationary Li-ion batteries are required to deal with unexpected power fluctuation in the electricity grid. Therefore a safe and continuous service is expected from this kind of asset.

The operation phase starts from the moment when the battery system is fully integrated in the electricity grid and all procedures related with its installation are concluded.

Table 12 and Table 13 of section 6 present all the information collected and results obtained from the risk analysis performed for the internal problem analysis and the external peril analysis.

4.6 Maintenance/Periodic Inspection

Periodic inspection and maintenance require careful considerations to ensure that the return to the operational stage occurs as planned. The personnel involved in these stages must be trained and technically prepared to successfully perform inspection and maintenance tasks. Also machinery and utilities used during inspection and maintenance should not damage the battery modules and the manoeuvres performed should not affect the module integrity as well as the neighbouring equipment.

Periodic inspection is performed to ensure that the battery modules are operating as expected. The evaluation must be performed by trained personnel, without compromising the normal operation of the modules. It is performed with specified time intervals, depending on the operator planning. This process typically consists in several visual and physical inspections executed according to a pre-set schedule.

The maintenance stage consists in replacing or adjusting pre-selected components that failed or are potential targets for failure. The removal of the pre-selected elements must not compromise or damage other components. Safety procedures and technical supervision are crucial at this stage.

Table 14 and Table 15 of section 6 present all the information collected and results obtained from the risk analysis performed for the internal problem analysis and the external peril analysis.

5. Conclusions

In this work, a risk analysis to stationary Li-ion batteries has been performed. The risk analysis had as main objective analysing the variety of hazards and dangerous situations that might be experienced by the battery during its life cycle and providing useful information on how to prevent or manage those undesired events.

The methodology used was based on the mapping of the identified risks (mechanical, chemical, electrical, thermodynamic, radiations, biologic and environmental hazards) in the different stages of the battery life cycle (production, storage, transportation, installation, operation, periodic inspections, maintenance, decommissioning and removal). Although the *Intensium® Max* batteries were used for this study, the methodology, as presented, can be easily adapted to other Li-ion batteries. However, some modifications may have to be made due to the battery system characteristics (*e.g.* modules and battery management system architecture). The methodology can also be adapted to batteries with other chemistries or even to other storage technologies, but more modifications are likely to be required.

During the risk analysis, it was found that building up a list of possible risks that compromises the well-being of the battery is rather complex. This list should include all technical, environmental and human aspects that may interfere with the battery, as well as all the battery internal problems that may result in an aggression over the surrounding environment. Taking this into consideration, two distinct analyses were performed for each stage of the battery life cycle: an internal problem analysis (battery internal problems that may result in an aggression over the surrounding environment) and an external peril analysis (external aggressions from the surrounding environment that may cause some battery

components failure).

For these analyses, the dangerous phenomena and the undesirable events resulting from each hazard was evaluated in terms of probability of occurrence and severity. Then, a risk assessment was carried out according to a predefined risk matrix. As several risks were found to be intolerable, a preliminary set of risk mitigation measures were proposed in order to reduce their probability of occurrence and/or their severity level. Afterwards, a new risk assessment was performed, this time considering that the risk mitigation measures were implemented. The results obtained from this new risk assessment showed that it is possible to reduce the probability of occurrence/severity of all the risks associated to the battery life cycle to acceptable or tolerable levels.

The probability of occurrence and severity level defined for some risks was based in theoretical reason, since there is still few data available related to large Li-ion batteries risks. With the increasing integration of these batteries in power systems, more data will be available in the future, being possible to update any eventual probability of occurrence or severity level that is not in accordance with reality. Still, it is worth noting that the validity of the methodology proposed remains intact and the outcomes of the analysis performed should be considered in the development of the safety tests to be proposed in the new standard.

Acknowledgements

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[21] SAFT Batteries, Intensium® Max Battery Technical Specifications. Available: http://www.saftbatteries.com/battery-search/intensium%C2%AE-max
[22] C. N. Ashtiani, “Battery Hazard Modes and Risk Mitigation Analysis”, USABC, Aug. 2007.

6. Risk Identification and Evaluation Tables

This section presents all the information collected and results obtained from the implementation of the risk analysis methodology. The results are presented in table format and are divided per stage of the battery life cycle. For each stage, two tables are presented: one for the internal problem analysis and the other for the external peril analysis.

6.1 Production Stage

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Weakened cell structure	Cell	Human error or technical failure	Future Failure	Incorrect quality evaluation	Electrolyte leakage	1	3	Acceptable	RMM06 RMM08	1	3	Acceptable
Overall production Quality	Cell	Human error or technical failure	Future Failure	Incorrect quality evaluation	Cell contamination	1	3	Acceptable	RMM06	1	3	Acceptable
Cell internal short-circuit during control process (charge)	Cell	Cell contamination	Thermal runaway	Incorrect quality evaluation	Toxic gas release / Fire	1	3	Acceptable	RMM06 RMM07	1	3	Acceptable
Bad assembly	Module	Human error or technical failure	Future Failure	Incorrect quality evaluation	Internal short-circuit on the module (equivalent to external short-circuit on cell)	1	3	Acceptable	RMM06	1	3	Acceptable
Bad conception regarding the constructive aspects	Container or Module	Human error or technical failure	Future Failure	Incorrect quality evaluation	Battery management failure, mechanical protection failure, electrical protection failure,...	1	3	Acceptable	RMM06	1	3	Acceptable

Table 5 – Risk identification and evaluation in the Production stage (*Internal Problem Analysis*)

6.2 Transportation/Removal Stages

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Flammable substances	Cell	Electrolyte leakage and inflammation	Battery or module fire	People in proximity	Burnt	2	3	Tolerable	RMM15 RMM16	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	4	Tolerable
Acidic or Corrosive substances	Cell	Electrolyte leakage with air exposition	Electrolyte leakage	Equipment in proximity	Corrosion	3	2	Tolerable	RMM12 RMM33	2	2	Acceptable
High temperature or Heat transfer source	Cell	Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions such as: cell over charge, charge after an over discharge, external short circuit on cell/module, internal short circuit on cell/module, etc.)	Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM01 RMM03 RMM17	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable		2	2	Acceptable
			Battery or module fire	People in proximity	Burnt	3	4	Intolerable	RMM04 RMM05 RMM06 RMM07 RMM08	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
High pressure	Cell	Thermal runaway (the cell can reach thermal runaway in case of abnormal conditions such as: cell over charge, charge after an over discharge, external short circuit on cell/module, internal short circuit on cell/module, etc.)	Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	2	2	Acceptable	RMM01 RMM02 RMM03 RMM15 RMM17	2	2	Acceptable
					Intoxication	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	2	2	Acceptable		2	2	Acceptable
			Battery or module fire	People in proximity	Burnt	2	4	Tolerable	RMM04 RMM05	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
	Container	Thermal runaway propagation inside the battery container or nitrogen release	Pressure rise in the container due to fire propagation or nitrogen release	-	Container over pressure	1	4	Tolerable	RMM19	1	4	Tolerable

Table 6 – Risk identification and evaluation in the Transportation/Removal stages (*Internal Problem Analysis*)

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Vibrations	Container	During transportation the battery container is subjected to vibrations	Deformation of the battery container or weakening of the metallic structure	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable	RMM20 RMM26 RMM32	1	4	Tolerable
				Loss of protection against external aggressions	External aggressions	3	2	Tolerable		2	2	Acceptable
Shock or drop	Container	During transportation the battery container is subjected to shock or drop	Deformation of the battery container or weakening of the	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable	RMM20 RMM21 RMM26	1	4	Tolerable

			metallic structure	Loss of protection against external aggressions	External aggressions	3	2	Tolerable	RMM32	2	2	Acceptable
	Module or Cell	Shock against a heavy object or drop	Electrolyte leakage	Equipment in proximity	Corrosion	3	2	Tolerable	RMM12 RMM33	2	2	Acceptable
			Asphyxiating gas, carcinogenic substance or Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	4	Intolerable	RMM02 RMM03 RMM24	1	3	Acceptable
			Module fire	Equipment in proximity	Fire propagation	3	4	Intolerable	RMM04 RMM05 RMM24	1	3	Acceptable
Stress, Compression	Container	During transportation the battery container can be subjected to compression	Deformation of the battery container	Pilling up of other containers upon it	Crush of the battery container	4	4	Intolerable	RMM20 RMM26	1	4	Tolerable
Sharp or cutting objects	Container	Shock against a sharp object	Deformation of the battery container or weakening of the metallic structure	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable	RMM20 RMM21	1	4	Tolerable
				Loss of protection against external aggressions	External aggressions	3	2	Tolerable		2	2	Acceptable
	Module or Cell	Impact against a heavy object	Electrolyte leakage	Equipment in proximity	Corrosion	3	2	Intolerable	RMM12 RMM24 RMM33	2	2	Acceptable
			Asphyxiating gas, carcinogenic substance or Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	4	Intolerable	RMM02 RMM03 RMM24	1	3	Acceptable
			Module fire	Equipment in proximity	Fire propagation	3	4	Intolerable	RMM04 RMM05 RMM24	1	3	Acceptable
Metal projection	Container	Projection of a metallic object against the battery container	Deformation of the battery container or weakening of the metallic structure	Pilling up of other containers upon it	Crush of the battery container	3	4	Intolerable	RMM20 RMM21	1	4	Tolerable
				Loss of protection against external aggressions	External aggressions	3	2	Tolerable		2	2	Acceptable
High temperature or Heat transfer source	Battery System, Module or Cell	High temperature induced by the environment(fire, external heat source) or heat radiation coming from the external environment	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Intoxication	2	2	Acceptable	-	2	2	Acceptable
					Asphyxia	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	2	2	Acceptable		2	2	Acceptable
			Module or battery fire	People in proximity	Burnt	2	3	Tolerable	RMM04 RMM05 RMM25	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
Humidity, condensation	Module or Cell	Water condensation inside the battery module	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM12 RMM24 RMM33	2	2	Acceptable
	Battery System	Water condensation inside the battery shelter	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM11 RMM12 RMM28 RMM33	2	2	Acceptable
			Insulation failure	People in contact with the battery	Electrical shock	4	2	Intolerable		2	2	Acceptable
Rain	Module	Water accumulation inside the battery modules	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM12 RMM24 RMM33	2	2	Acceptable
	Battery System	Water accumulation inside the battery container	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM12 RMM28 RMM33	2	2	Acceptable
Salt	Container	Accumulation of salt leading to the accelerated corrosion of the battery container	Weakening of the battery container	Loss of protection against external aggressions	External aggressions	3	2	Tolerable	RMM30 RMM32	2	2	Acceptable
	Battery System or Module	Accumulation of salt leading to the accelerated corrosion of the electronic boards or other metallic parts of the battery system	Weakening of the electronic boards or other metallic parts of the battery system	Equipment in proximity	Corrosion	3	2	Tolerable	RMM12 RMM30 RMM33	2	2	Acceptable
Sand and dust	Container	Exposure to sand and dust	Weakening of the battery container	Loss of protection against external aggressions	External aggressions	3	2	Tolerable	RMM32	2	2	Acceptable

Table 7 – Risk identification and evaluation in the Transportation/Removal stages (*External Peril Analysis*)

6.3 Installation/Decommissioning Stages

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Sharp or cutting objects	Container or Module	Cutting metallic parts of the container or modules are accessible and non-protected	Shock against a sharp object	People in proximity	Cuts and other injuries	3	2	Tolerable	RMM14	2	2	Acceptable
Flammable substances	Cell	Electrolyte leakage and inflammation	Battery or module fire	People in proximity	Burnt	2	3	Tolerable	RMM15 RMM16	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	4	Tolerable
Acidic or Corrosive substances	Cell	Electrolyte leakage with air exposition	Electrolyte leakage	Equipment in proximity	Corrosion	3	2	Tolerable	RMM12 RMM33	2	2	Acceptable

Carcinogenic substances	Cell	Thermal runaway (the cell can reach thermal runaway in case of abnormal conditions)	Carcinogenic substances release	People in proximity	Intoxication	3	2	Tolerable	RMM01 RMM15 RMM17	2	2	Acceptable
Toxic substances	Cell	Electrolyte leakage with humidity exposition	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM01 RMM15 RMM17	3	1	Acceptable
Asphyxiating substances	Cell	Thermal runaway (the cell can reach thermal runaway in case of abnormal conditions)	Asphyxiating substances release	People in proximity	Intoxication	3	2	Tolerable	RMM01 RMM15 RMM17	2	2	Acceptable
	Nitrogen	Nitrogen release (used to contain fire)	Asphyxiating substance release	People in proximity	Asphyxia	4	2	Intolerable	RMM13 RMM17	2	2	Acceptable
High voltage (>120V)	Battery System or Array of Modules	High voltage (ca. 800 to 1000V for Array of Modules)	High voltage	People in contact with the battery	Electrical shock	4	2	Intolerable	RMM17	2	2	Acceptable
High current	Array of Modules	High current delivered by the battery system	High current	People in contact with the battery	Electrical shock	4	2	Intolerable	RMM17	2	2	Acceptable
High temperature or Heat transfer source	Cell	Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions such as: cell over charge, charge after an over discharge, external short circuit on cell/module, internal short circuit on cell/module, etc.)	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM12 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM01 RMM03 RMM17	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	3	2	Tolerable		2	2	Acceptable
			Battery or module fire	People in proximity	Burnt	3	3	Intolerable	RMM04 RMM05 RMM06 RMM07 RMM08 RMM17	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
High pressure	Cell	Failure of the venting system or internal cell short circuit	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
		Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions such as: cell over charge, charge after an over discharge, external short circuit on cell/module, internal short circuit on cell/module, etc.)	Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	2	2	Acceptable	RMM01 RMM02 RMM03 RMM15 RMM17	2	2	Acceptable
					Intoxication	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	2	2	Acceptable		2	2	Acceptable
			Battery or module fire	People in proximity	Burnt	2	3	Tolerable	RMM04 RMM05 RMM17	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
	Container	Thermal runaway propagation inside the battery container or nitrogen release	Pressure rise in the container due to fire or nitrogen release	-	Container over pressure	1	4	Tolerable	RMM19	1	4	Tolerable

Table 8 – Risk identification and evaluation in the Installation/Decommissioning stages (*Internal Problem Analysis*)

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Vibrations	Container	During installation/ decommissioning activity the battery container is subjected to vibrations	Deformation of the battery container or weakening of the metallic structure	Loss of protection against external aggressions	External aggressions	3	2	Tolerable	RMM20 RMM26 RMM32	2	2	Acceptable
Shock or drop	Container	During installation/decommissioning the battery container is subjected to a shock	Deformation of the battery container or weakening of the metallic structure	Loss of protection against external aggressions	External aggressions	3	2	Tolerable	RMM18 RMM20 RMM26 RMM32	2	2	Acceptable
	Battery System Module or Cell	Shock against a heavy object	Electrolyte leakage	People in proximity	Intoxication	4	1	Tolerable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	4	2	Intolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	4	2	Intolerable	RMM02 RMM03 RMM17	2	2	Acceptable
					Intoxication	4	2	Intolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	4	2	Intolerable		2	2	Acceptable
			Module or Battery fire	People in proximity	Burnt	4	3	Intolerable	RMM04 RMM05 RMM17	1	3	Acceptable
				Equipment in proximity	Fire propagation	4	4	Intolerable		1	3	Acceptable
Sharp or cutting objects	Container	Shock against a sharp object	Deformation of the battery container or weakening of the metallic structure	Loss of protection against external aggressions	External aggressions	3	2	Tolerable	RMM18	2	2	Acceptable
	Battery System, Module or Cell	Impact against a heavy object	Electrolyte leakage	People in proximity	Intoxication	4	1	Tolerable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	4	2	Intolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	4	2	Intolerable	RMM02 RMM03 RMM17	2	2	Acceptable
					Intoxication	4	2	Intolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	4	2	Intolerable		2	2	Acceptable
			Module or battery fire	People in proximity	Burnt	4	3	Intolerable	RMM04 RMM05	1	3	Acceptable

				Equipment in proximity	Fire propagation	4	4	Intolerable	RMM17	1	3	Acceptable
Metal projection	Container	Projection of a metallic object against the battery container	Deformation of the battery container or weakening of the metallic structure	Loss of protection against external aggressions	External aggressions	3	2	Tolerable	RMM17 RMM18	2	2	Acceptable
Electrostatic energy	Electronic Boards	Electrostatic discharge during boards handling	Electrostatic discharge	Equipment in proximity	Electronic damage	4	2	Intolerable	RMM36	2	2	Acceptable
High temperature or Heat transfer source	Battery System, Module or Cells	High temperature induced by the environment (fire, external heat source) or heat radiation coming from the external environment	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Intoxication	2	2	Acceptable	-	2	2	Acceptable
					Asphyxia	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	2	2	Acceptable		2	2	Acceptable
			Module or battery fire	People in proximity	Burnt	2	3	Tolerable	RMM04 RMM05 RMM25	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
Vermin and other animals	Battery System	Vermin or animals existing in the environment which enter inside the battery container	Isolation failure	People in contact with the battery	Electrical shock	3	3	Intolerable	RMM11 RMM17 RMM26	1	3	Acceptable
Humidity, condensation	Module or Cell	Water condensation inside the battery module	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM12 RMM17 RMM33	2	2	Acceptable
	Battery System	Water condensation inside the battery shelter	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM11 RMM12 RMM17 RMM33	2	2	Acceptable
			Insulation failure	People in contact with the battery	Electrical shock	4	3	Intolerable		1	3	Acceptable
Rain	Module	Water accumulation inside the battery modules	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM12 RMM17 RMM33	2	2	Acceptable
Sand and dust	Container	Exposure to sand and dust	Weakening of the battery container	Loss of protection against external aggressions	External aggressions	3	2	Tolerable	RMM32	2	2	Acceptable

Table 9 – Risk identification and evaluation in the Installation/Decommissioning stages (*External Peril Analysis*)

6.4 Storage Stage

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Sharp or cutting objects	Container or Module	Cutting metallic parts of the container or modules are accessible and non-protected	Shock against a sharp object	People in proximity	Cuts and other injuries	3	2	Tolerable	RMM14	2	2	Acceptable
Flammable substances	Cell	Electrolyte leakage and inflammation	Battery or module fire	People in proximity	Burnt	2	3	Tolerable	RMM15 RMM16	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	4	Tolerable
Acidic or Corrosive substances	Cell	Electrolyte leakage with air exposition	Electrolyte leakage	Equipment in proximity	Corrosion	3	2	Tolerable	RMM12 RMM33	2	2	Acceptable
Carcinogenic substances	Cell	Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions)	Carcinogenic substances release	People in proximity	Intoxication	3	2	Tolerable	RMM01 RMM15 RMM17	2	2	Acceptable
Toxic substances	Cell	Electrolyte leakage with humidity exposition	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM01 RMM15 RMM17	3	1	Acceptable
Asphyxiating substances	Cell	Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions)	Asphyxiating substances release	People in proximity	Intoxication	3	2	Tolerable	RMM01 RMM15 RMM17	2	2	Acceptable
	Nitrogen	Nitrogen release (used to contain fire)	Asphyxiating substance release	People in proximity	Asphyxia	4	2	Intolerable	RMM13 RMM17	2	2	Acceptable
High voltage (>120V)	Battery System or Array of Modules	High voltage (ca. 800 to 1000V for Array of Modules)	High voltage	People in contact with the battery	Electrical shock	4	2	Intolerable	RMM17	2	2	Acceptable
High current	Array of Modules	High current delivered by the battery system	High current	People in contact with the battery	Electrical shock	4	2	Intolerable	RMM17	2	2	Acceptable
High temperature or Heat transfer source	Cell	Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions such as: cell over charge, charge after an over discharge, external short circuit on cell/module, internal short circuit on cell/module, etc.)	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM12 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM01 RMM03 RMM17	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable		2	2	Acceptable
			Battery or module fire	People in proximity	Burnt	3	3	Intolerable	RMM04 RMM05 RMM06 RMM07 RMM08	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
High pressure	Cell	Failure of the venting system or internal cell short circuit	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable

		Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions such as: cell over charge, charge after an over discharge, external short circuit on cell/module, internal short circuit on cell/module, etc.)	Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	2	2	Acceptable	RMM01 RMM02 RMM03 RMM15 RMM17	2	2	Acceptable
					Intoxication	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	2	2	Acceptable		2	2	Acceptable
			Battery or module fire	People in proximity	Burnt	2	3	Tolerable	RMM04 RMM05	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
	Container	Thermal runaway propagation inside the battery container or nitrogen release	Pressure rise in the container due to fire propagation or nitrogen release	-	Container over pressure	1	4	Tolerable	RMM19	1	4	Tolerable

Table 10 – Risk identification and evaluation in the Storage stage (*Internal Problem Analysis*)

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Vibrations	Container	During seismic activity the battery container is subjected to vibrations	Deformation of the battery container or weakening of the metallic structure	Loss of protection against external aggressions	External aggressions	1	2	Acceptable	RMM20 RMM26 RMM32	1	2	Acceptable
Shock	Container	During storage the battery container is subjected to a shock	Deformation of the battery container or weakening of the metallic structure	Loss of protection against external aggressions	External aggressions	2	2	Acceptable	RMM22	2	2	Acceptable
	Battery System, Module or Cell	Shock against a heavy object	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM12 RMM22 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	4	2	Intolerable	RMM02 RMM03 RMM17	2	2	Acceptable
					Intoxication	4	2	Intolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	4	2	Intolerable		2	2	Acceptable
			Module or Battery fire	People in proximity	Burnt	4	3	Intolerable	RMM04 RMM05 RMM17	1	3	Acceptable
				Equipment in proximity	Fire propagation	4	4	Intolerable		1	3	Acceptable
Sharp or cutting objects	Container	Shock against a sharp object	Deformation of the battery container or weakening of the metallic structure	Loss of protection against external aggressions	External aggressions	2	2	Acceptable	RMM22	2	2	Acceptable
	Battery System, Module or Cell	Impact against a heavy object	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM12 RMM22 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM02 RMM03 RMM22	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable		2	2	Acceptable
			Module or battery fire	People in proximity	Burnt	3	3	Intolerable	RMM04 RMM05 RMM22	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
Metal projection	Container	Projection of a metallic object against the battery container	Deformation of the battery container or weakening of the metallic structure	Loss of protection against external aggressions	External aggressions	3	2	Tolerable	RMM22	2	2	Acceptable
High Voltage	Module or Cell	During storage of modules, as spare parts, some charge could be done. Failure in charger or not appropriate charger.	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM12 RMM17 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM02 RMM03 RMM17	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable		2	2	Acceptable
			Module fire	People in proximity	Burnt	3	3	Intolerable	RMM04 RMM05 RMM17 RMM31 RMM35	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
High Current	Module or Cell	During storage of modules, as spare parts, some charge could be done. Failure in charger or not appropriate charger.	Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM41 RMM04 RMM05 RMM35	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable		2	2	Acceptable
			Module fire	People in proximity	Burnt	3	3	Intolerable	RMM03 RMM04 RMM05 RMM35	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
High temperature or Heat transfer source	Battery System, Module or Cell	High temperature induced by the environment (fire, external heat source) or heat radiation coming from the external environment	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Intoxication	2	2	Acceptable	-	2	2	Acceptable
					Asphyxia	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	2	2	Acceptable		2	2	Acceptable
			Module or battery fire	People in proximity	Burnt	2	3	Tolerable	RMM04 RMM05 RMM25	2	2	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		2	2	Acceptable

Vermin and other animals	Container	Animals existing in the environment which enter inside the battery container	Weakening of the battery container	Loss of protection	External aggressions	3	2	Tolerable	RMM26	2	2	Acceptable
	Battery System	Vermin or animals existing in the environment which enter inside the battery container	Isolation failure	People in contact with the battery	Electrical shock	3	3	Intolerable	RMM11 RMM22 RMM26	1	3	Acceptable
Humidity, condensation	Module or Cell	Water condensation inside the battery module	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM12 RMM27 RMM33	2	2	Acceptable
	Battery System	Water condensation inside the battery shelter	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM11 RMM12 RMM33	2	2	Acceptable
			Insulation failure	People in contact with the battery	Electrical shock	4	3	Intolerable		1	3	Acceptable
Flood	Module or Cell	Flood during storage of the module	Flooding	Equipment in proximity	H_2 generation	2	4	Intolerable	RMM27	1	4	Tolerable
	Battery System	Water accumulation in the battery container	Flooding	Equipment in proximity	H_2 generation	2	4	Intolerable	RMM29	2	3	Tolerable
			Insulation failure	People in contact with the battery	Electrical shock	2	3	Tolerable		2	3	Tolerable
Rain	Module	Water accumulation inside the battery modules	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM12 RMM27 RMM33	2	2	Acceptable
	Battery System	Water accumulation inside the battery container	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM11 RMM12 RMM33	2	2	Acceptable
			Insulation failure	People in contact with the battery	Electrical shock	4	3	Intolerable		1	3	Acceptable
Salt	Container	Accumulation of salt leading to the corrosion of the battery container	Weakening of the battery container	Loss of protection	External aggressions	3	2	Tolerable	RMM30 RMM32	2	2	Acceptable
	Battery System or Module	Accumulation of salt leading to the accelerated corrosion of the electronic boards or other metallic parts of the battery system	Weakening of the electronic boards or other metallic parts of the battery system	Equipment in proximity	Corrosion	3	2	Tolerable	RMM12 RMM30 RMM32 RMM33	2	2	Acceptable
Sand and dust	Container	Exposure to sand and dust	Weakening of the battery container	Loss of protection against external aggressions	External aggressions	3	2	Tolerable	RMM32	2	2	Acceptable

Table 11 – Risk identification and evaluation in the Storage stage (*External Peril Analysis*)

6.5 Operation Stage

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Mobile or rotary component	EESUs fans	Rotational behaviour of the fans while functioning	Rotary Component	People in proximity	Cuts and other injuries	3	2	Tolerable	RMM23 RMM35	2	2	Acceptable
Sharp or cutting objects	Container or Module	Cutting metallic parts of the container or modules are accessible and non-protected	Shock against a sharp object	People in proximity	Cuts and other injuries	3	2	Tolerable	RMM14	2	2	Acceptable
Flammable substances	Cell	Electrolyte leakage and inflammation	Battery or module fire	People in proximity	Burnt	2	3	Tolerable	RMM15 RMM16	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	4	Tolerable
Acidic or Corrosive substances	Cell	Electrolyte leakage with air exposition	Electrolyte leakage	Equipment in proximity	Corrosion	3	2	Tolerable	RMM12 RMM33	2	2	Acceptable
Carcinogenic substances	Cell	Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions)	Carcinogenic substances release	People in proximity	Intoxication	3	2	Tolerable	RMM01 RMM15 RMM17	2	2	Acceptable
Toxic substances	Cell	Electrolyte leakage with humidity exposition	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM01 RMM15 RMM17	3	1	Acceptable
Asphyxiating substances	Cell	Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions)	Asphyxiating substances release	People in proximity	Intoxication	3	2	Tolerable	RMM01 RMM15 RMM17	2	2	Acceptable
	Nitrogen	Nitrogen release (used to contain fire)	Asphyxiating substance release	People in proximity	Asphyxia	4	2	Intolerable	RMM13 RMM17	2	2	Acceptable
High voltage (>120V)	Battery System or Array of Modules	High voltage (ca. 800 to 1000V for Array of Modules)	High voltage	People in contact with the battery	Electrical shock	4	2	Intolerable	RMM17	2	2	Acceptable
High current	Array of Modules	High current delivered by the battery	High current	People in contact	Electrical shock	4	2	Intolerable	RMM17	2	2	Acceptable
High temperature or Heat transfer source	Module or Cell	Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions such as: cell over charge, charge after an over discharge, external short circuit on cell/module, internal short circuit on cell/module, etc.)	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM12 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM01 RMM03 RMM17	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	3	2	Tolerable		2	2	Acceptable
			Battery or module fire	People in proximity	Burnt	3	3	Intolerable	RMM04 RMM05 RMM06 RMM07 RMM08 RMM17	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
High pressure	Cell	Failure of the venting system or internal cell short circuit	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
		Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions such	Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	2	2	Acceptable	RMM01 RMM02 RMM03	2	2	Acceptable
					Intoxication	2	2	Acceptable		2	2	Acceptable

		as: cell over charge, charge after an over discharge, external short circuit on cell/module, internal short circuit on cell/module, etc.)	Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	2	2	Acceptable	RMM15 RMM17	2	2	Acceptable
			Battery or module fire	People in proximity	Burnt	2	3	Tolerable	RMM04 RMM05	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
	container	Thermal runaway propagation inside battery container or nitrogen release	Pressure rise in the container due to fire propagation or nitrogen release	-	Container over pressure	4	4	Intolerable	RMM19	1	4	Tolerable
Overheat	Cell	Bad Connections, fault in cell	Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	4	2	Intolerable	RMM37 RMM01 RMM02	2	2	Acceptable
					Intoxication	4	2	Intolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	4	2	Intolerable	RMM37 RMM03	2	2	Acceptable
			Electrolyte leakage	People in proximity	Intoxication	4	1	Tolerable	RMM37 RMM12 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	4	2	Intolerable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	4	3	Intolerable	RMM37 RMM04 RMM05	2	2	Acceptable
				Equipment in proximity	Fire propagation	4	4	Intolerable		1	3	Acceptable
	Battery System	Bad battery cooling, high number of cycling or failure of the air conditioning system	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
			Asphyxiating gas, carbon powder or other carcinogenic substance release	People in proximity	Asphyxia	2	2	Acceptable	RMM01 RMM02 RMM03	2	2	Acceptable
					Intoxication	2	2	Acceptable		2	2	Acceptable
				Equipment in proximity	Pollution surr. equip.	2	2	Acceptable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	2	3	Tolerable	RMM40 RMM04 RMM05	2	2	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
Over charge	Cell	Failure in Battery Management	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM38 RMM12 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	4	2	Intolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM01 RMM02 RMM03	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	4	2	Intolerable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	3	3	Intolerable	RMM38 RMM04 RMM05	2	2	Acceptable
				Equipment in proximity	Fire propagation	4	4	Intolerable		1	3	Acceptable
Forced discharge (U<0 – polarity reversal)[1]	Module or Cell	Failure in Battery Management	-	-	-	-	-	-	RMM43	-	-	-
Recharge of an over discharged cell	Cell	Failure in Battery Management	Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM39 RMM01 RMM02 RMM03 RMM31	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	3	3	Intolerable	RMM39 RMM04 RMM05	2	2	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
Loss of cell tightness	Cell	Failure between the rivet and the hole to fill the cell or weakness of the venting system	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM11	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Insulation fault	People in contact	Electrical shock	3	3	Intolerable		1	3	Acceptable
Internal short circuit	Cell	Production failure that results in internal short circuit with possible thermal runaway	Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM01 RMM02 RMM06 RMM07 RMM08	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable	RMM03	2	2	Acceptable
			Battery fire	People in proximity	Burnt	3	3	Intolerable	RMM04 RMM05 RMM06 RMM07 RMM08	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
	Module	Module internal short circuit (equivalent to a cell external short)	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM12 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM01 RMM02 RMM03	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	3	3	Intolerable	RMM04 RMM05	1	3	Acceptable

[1] When there is a forced discharge the cell voltage polarity is inverted. In order to verify there is no dangerous phenomenon during the discharge phase, tests during cell voltage inversion at nominal discharge current should be performed.

				Equipment in proximity	Fire propagation	3	4	Intolerable	RMM09 RMM34	1	3	Acceptable
	Array of Modules	An Array of Modules internal short circuit is equivalent to a module external short	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	2	2	Acceptable	RMM01 RMM02 RMM03	2	2	Acceptable
					Intoxication	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	2	2	Acceptable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	2	3	Tolerable	RMM41 RMM04 RMM05 RMM10 RMM34	2	2	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
	Battery System	A battery system internal short is equivalent to a module external or internal short or a Array of Modules external or internal short	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	2	2	Acceptable	RMM01 RMM02 RMM03	2	2	Acceptable
					Intoxication	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	2	2	Acceptable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	2	3	Tolerable	RMM41 RMM04 RMM05 RMM10 RMM34	2	2	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
External short circuit	Cell	Bus bar or another electronic component in short circuit	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM12 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM01 RMM02 RMM03	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	3	3	Intolerable	RMM04 RMM05 RMM09 RMM34	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
	Module	External short circuit between one or several modules caused by bad assembly or short circuit on bus bar	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	2	2	Acceptable	RMM01 RMM02 RMM03	2	2	Acceptable
					Intoxication	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	2	2	Acceptable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	2	3	Tolerable	RMM41 RMM04 RMM05 RMM10 RMM34	2	2	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
	Module	Bad assembly or a short circuit on the Battery Management Module	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	2	2	Acceptable	RMM01 RMM02 RMM03	2	2	Acceptable
					Intoxication	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	2	2	Acceptable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	2	3	Tolerable	RMM41 RMM04 RMM05 RMM10 RMM34	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		2	2	Acceptable
Fire propagation in the battery container	Battery System	Failure of the suppression system	Battery fire	People in proximity	Burnt	1	3	Acceptable	RMM04 RMM05	1	3	Acceptable
				Equipment in proximity	Fire propagation	1	4	Tolerable		1	3	Acceptable
			Nitrogen release	People in proximity	Asphyxia	4	2	Intolerable	RMM13	2	2	Acceptable

Table 12 – Risk identification and evaluation in the Operation stage (*Internal Problem Analysis*)

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Vibrations	Container	During seismic activity the battery container is subjected to vibrations	Deformation of the battery container	Loss of protection	External aggressions	1	2	Acceptable	RMM20 RMM26 RMM32	1	2	Acceptable
Shock	Container	During operation the battery container is subjected to a shock	Deformation of the battery container	Loss of protection	External aggressions	2	2	Acceptable	RMM23	2	2	Acceptable
	Battery System	Shock against a heavy object of a module/cell during operation phase (human error)	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM12 RMM23 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM01 RMM02 RMM03	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable

			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable	RMM15 RMM23	2	2	Acceptable
			Battery fire	People in proximity	Burnt	3	3	Intolerable	RMM04 RMM05 RMM23	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
Sharp or cutting objects	Container	Shock against a sharp object	Deformation of the battery container	Loss of protection s	External aggressions	2	2	Acceptable	RMM23	2	2	Acceptable
	Battery System	Shock against a sharp object	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM01 RMM12 RMM15 RMM17 RMM23 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM01 RMM02 RMM03 RMM15 RMM17 RMM23	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	3	3	Intolerable	RMM04 RMM05 RMM17 RMM23	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
Metal projection	Container	Projection of a metallic object against the battery container	Deformation of the battery container	Loss of protection	External aggressions	3	2	Tolerable	RMM23	2	2	Acceptable
High Voltage	Battery System	High voltage from external or failure in charger	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM38 RMM12 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM38 RMM01 RMM02 RMM03 RMM15	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	3	3	Intolerable	RMM38 RMM04 RMM05 RMM17	2	2	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
High Current	Battery System	High current from external or failure in charger or an external short circuit or overload	Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM41 RMM01 RMM02 RMM03 RMM15	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	3	2	Tolerable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	3	3	Intolerable	RMM41 RMM04 RMM05 RMM17	2	2	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
Electromagnetic radiation	Electronic Board	Electromagnetic from surrounding environment or external sources	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM42	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable		2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	3	2	Tolerable		2	2	Acceptable
			Battery fire	People in proximity	Burnt	3	3	Intolerable	RMM38 RMM04 RMM05 RMM17	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
High temperature or Heat transfer source	Battery System, Module or Cells	High temperature induced by the environment (fire, external heat source) or heat radiation coming from the external environment	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Intoxication	2	2	Acceptable	-	2	2	Acceptable
					Asphyxia	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	2	2	Acceptable		2	2	Acceptable
			Module or battery fire	People in proximity	Burnt	2	3	Tolerable	RMM04 RMM05	2	3	Tolerable
				Equipment in proximity	Fire propagation	2	4	Intolerable		2	3	Tolerable
Vermin and other animals	Container	Vermin or animals existing in the environment which enter inside the battery container	Weakening of the battery container	Loss of protection against external aggressions	External aggressions	3	2	Tolerable	RMM26	2	2	Acceptable
	Battery System	Vermin or animals existing in the environment which enter inside the battery container	Isolation failure	People in contact with the battery	Electrical shock	3	3	Intolerable	RMM11 RMM23 RMM26	1	3	Acceptable
Humidity, condensation	Module or Cell	Water condensation inside the battery module	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM11 RMM12 RMM17 RMM33	2	2	Acceptable
	Battery System	Water condensation inside the battery shelter or failure of the air conditioning system	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable		2	2	Acceptable
			Insulation failure	People in contact with the battery	Electrical shock	4	3	Intolerable		1	3	Acceptable
Flood	Battery System	Water accumulation in the battery container	Flooding	Equipment in proximity	H_2 generation	2	4	Intolerable	RMM11 RMM29	1	4	Tolerable
			Insulation failure	People in contact	Electrical shock	2	3	Intolerable		1	3	Acceptable
Rain	Module	Water accumulation inside the battery modules	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM11 RMM12 RMM33	2	2	Acceptable
	Battery System	Water accumulation inside the battery container	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable		2	2	Acceptable

			Insulation failure	People in contact with the battery	Electrical shock	4	3	Intolerable		1	3	Acceptable
Lightening	Battery System	High current can damage the electronic components	Battery fire	Equipment in proximity	Fire propagation	3	4	Intolerable	RMM04 RMM05	2	3	Tolerable
Salt	Container	Accumulation of salt leading to the corrosion of the battery container	Weakening of the battery container	Loss of protection	External aggressions	3	2	Tolerable	RMM30 RMM32	2	2	Acceptable
	Battery System or Module	Accumulation of salt leading to the accelerated corrosion of the electronic boards or other metallic parts of the battery system	Weakening of the electronic boards or other metallic parts of the battery system	Equipment in proximity	Corrosion	3	2	Tolerable	RMM12 RMM30 RMM32 RMM33	2	2	Acceptable
Sand and dust	Container	Exposure to sand and dust	Weakening of the container	Loss of protection	External aggressions	3	2	Tolerable	RMM32	2	2	Acceptable

Table 13 – Risk identification and evaluation in the Operation stage (*External Peril Analysis*)

6.6 Maintenance/Periodic Inspection Stages

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Mobile or rotary component	EESUs fans	Rotational behaviour of the fans while functioning	Rotary Component	People in proximity	Cuts and other injuries	3	2	Tolerable	RMM23 RMM35	1	2	Acceptable
Sharp or cutting objects	Container or Module	Cutting metallic parts of the container or modules are accessible and non-protected	Shock against a sharp object	People in proximity	Cuts and other injuries	3	2	Tolerable	RMM14	2	2	Acceptable
Flammable substances	Cell	Electrolyte leakage and inflammation	Battery or module fire	People in proximity	Burnt	2	3	Tolerable	RMM15 RMM16	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	4	Tolerable
Acidic or Corrosive substances	Cell	Electrolyte leakage with air exposition	Electrolyte leakage	Equipment in proximity	Corrosion	3	2	Tolerable	RMM12 RMM33	2	2	Acceptable
Carcinogenic substances	Cell	Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions)	Carcinogenic substances release	People in proximity	Intoxication	3	2	Tolerable	RMM01 RMM15 RMM17	2	2	Acceptable
Toxic substances	Cell	Electrolyte leakage with humidity exposition	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM01 RMM15 RMM17	3	1	Acceptable
Asphyxiating substances	Cell	Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions)	Asphyxiating substances release	People in proximity	Intoxication	3	2	Tolerable	RMM01 RMM15 RMM17	2	2	Acceptable
	Nitrogen	Nitrogen release (used to contain fire)	Asphyxiating substance release	People in proximity	Asphyxia	4	2	Intolerable	RMM13 RMM17	2	2	Acceptable
High voltage (>120V)	Array of Modules or Battery System	High voltage (ca. 800 to 1000V for Array of Modules)	High voltage	People in contact with the battery	Electrical shock	4	2	Intolerable	RMM17 RMM18	2	2	Acceptable
High current	Array of Modules	High current delivered by the battery	High current	People in contact	Electrical shock	4	2	Intolerable	RMM17	2	2	Acceptable
High temperature or Heat transfer source	Cell	Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions such as: cell over charge, charge after an over discharge, external short circuit on cell/module, internal short circuit on cell/module, etc.)	Electrolyte leakage	People in proximity	Intoxication	3	1	Acceptable	RMM12 RMM33	3	1	Acceptable
				Equipment in proximity	Corrosion	3	2	Tolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	3	2	Tolerable	RMM01 RMM03 RMM17	2	2	Acceptable
					Intoxication	3	2	Tolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	3	2	Tolerable		2	2	Acceptable
			Battery or module fire	People in proximity	Burnt	3	3	Intolerable	RMM04 RMM05 RMM06 RMM07 RMM08 RMM17	1	3	Acceptable
				Equipment in proximity	Fire propagation	3	4	Intolerable		1	3	Acceptable
High pressure	Cell	Failure of the venting system or internal cell short circuit	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
		Thermal Runaway (the cell can reach thermal runaway in case of abnormal conditions such as: cell over charge, charge after an over discharge, external short circuit on cell/module, internal short circuit on cell/module, etc.)	Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	2	2	Acceptable	RMM01 RMM02 RMM03 RMM15 RMM17	2	2	Acceptable
					Intoxication	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution of surrounding equipment	2	2	Acceptable		2	2	Acceptable
			Battery or module fire	People in proximity	Burnt	2	3	Tolerable	RMM04 RMM05 RMM17	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
	Container	Thermal runaway or nitrogen release	Pressure rise in container due to fire propagation or nitrogen release	-	Container over pressure	4	4	Intolerable	RMM19	1	4	Tolerable

Table 14 – Risk identification and evaluation in the Maintenance/Periodic Inspection stages (*Internal Problem Analysis*)

Hazard	Element	Causes	Dangerous Occurrence	Dangerous Situation	Undesirable Event	P	S	RA	RMM	P_{RMM}	S_{RMM}	RA_{RMM}
Shock or Drop	Container	The Container is subjected to shock	Deformation of battery container	Loss of protection	External aggressions	2	2	Acceptable	RMM23	2	2	Acceptable
	Battery System, Module or Cell	Shock against a heavy object	Electrolyte leakage	People in proximity	Intoxication	4	1	Tolerable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	4	2	Intolerable		2	2	Acceptable
			Asphyxiating gas or	People in	Asphyxia	4	2	Intolerable	RMM02	2	2	Acceptable

			other carcinogenic substance release	proximity	Intoxication	4	2	Intolerable	RMM03 RMM17	2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	4	2	Intolerable		2	2	Acceptable
			Module or Battery fire	People in proximity	Burnt	4	3	Intolerable	RMM04 RMM05 RMM17	1	3	Acceptable
				Equipment in proximity	Fire propagation	4	4	Intolerable		1	3	Acceptable
Sharp or cutting objects	Container	Shock against a sharp object	Deformation of the battery container	Loss of protection	External aggressions	2	2	Acceptable	RMM17	2	2	Acceptable
	Battery System, Module or Cell	Impact against a heavy object	Electrolyte leakage	People in proximity	Intoxication	4	1	Tolerable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	4	2	Intolerable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Asphyxia	4	2	Intolerable	RMM02 RMM03 RMM17	2	2	Acceptable
					Intoxication	4	2	Intolerable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	4	2	Intolerable		2	2	Acceptable
			Module or battery fire	People in proximity	Burnt	4	3	Intolerable	RMM04 RMM05 RMM17	1	3	Acceptable
				Equipment in proximity	Fire propagation	4	4	Intolerable		1	3	Acceptable
Metal projection	Container	Projection of a metallic object	Deformation of the battery container	Loss of protection	External aggressions	3	2	Tolerable	RMM17	2	2	Acceptable
Electrostatic energy	Electronic Boards	ESD during boards handling	Electrostatic discharge (ESD)	Equipment in proximity	Electronic damage	4	2	Intolerable	RMM36	2	2	Acceptable
High temperature or Heat transfer source	Battery System, Module or Cells	High temperature induced by the environment (fire, external heat source) or heat radiation coming from external environment	Electrolyte leakage	People in proximity	Intoxication	2	1	Acceptable	RMM12 RMM17 RMM33	2	1	Acceptable
				Equipment in proximity	Corrosion	2	2	Acceptable		2	2	Acceptable
			Asphyxiating gas or other carcinogenic substance release	People in proximity	Intoxication	2	2	Acceptable	-	2	2	Acceptable
					Asphyxia	2	2	Acceptable		2	2	Acceptable
			Carbon powder release	Equipment in proximity	Pollution surr. equip.	2	2	Acceptable		2	2	Acceptable
			Module or battery fire	People in proximity	Burnt	2	3	Tolerable	RMM04 RMM05 RMM25	1	3	Acceptable
				Equipment in proximity	Fire propagation	2	4	Intolerable		1	3	Acceptable
Vermin and other animals	Battery System	Vermin or animals existing in the environment which enter inside the battery container	Isolation failure	People in contact with the battery	Electrical shock	3	3	Intolerable	RMM11 RMM17 RMM26	1	3	Acceptable
Humidity, condensation	Module or Cell	Water condensation inside the module	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM11 RMM12 RMM17 RMM33	2	2	Acceptable
	Battery System	Water condensation inside the battery shelter	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable		2	2	Acceptable
			Insulation failure	People in contact with the battery	Electrical shock	4	3	Intolerable		1	3	Acceptable
Rain	Module	Water accumulation inside the modules	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable	RMM11 RMM12 RMM33	2	2	Acceptable
	Battery System	Water accumulation inside the battery container	Humidity	Equipment in proximity	Corrosion	4	2	Intolerable		2	2	Acceptable
			Insulation failure	People in contact with the battery	Electrical shock	4	3	Intolerable		1	3	Acceptable
Sand and dust	Container	Exposure to sand and dust	Weakening of the container	Loss of protection	External aggressions	3	2	Tolerable	RMM32	2	2	Acceptable

Table 15 – Risk identification and evaluation in the Maintenance/Periodic Inspection stages (*External Peril Analysis*)

7. Risk Mitigation Measures

	Description	Classification	Risk/Undesirable Event
RMM01	Determine the nature, volume and toxicity of the gas generated inside the battery container in case of gases being liberated from cells	Analysis and test	Intoxication and asphyxia
RMM02	Carry out analyses to show that in case of cell overpressure, the cells venting is correctly functioning	Analysis and test	Cell venting
RMM03	Carry out analyses to identify the risk of electrical hazards due to carbon powder release (safety distance to avoid the creation of electrical arcs)	Analysis	Pollution of surrounding equipment
RMM04	Implement a thermal barrier against thermal runaway propagation between cells inside the module in case of fire on one cell	Thermal protection	Fire propagation
RMM05	Implement a thermal barrier to avoid fire contamination outside the module in case of fire on one cell	Thermal protection	Fire propagation
RMM06	Define a procedure for checking the defects during cell assembling	Quality check	Cell internal short circuit
RMM07	Carry out experiments to determine the conditions which lead to fire in case of cell internal short circuit	Analysis	Cell internal short circuit
RMM08	Carry out analyses to determine the level of leaking current corresponding to an internal short circuit on a cell	Test	Cell internal short circuit
RMM09	Use an electronic board design which avoids fire contamination on cell in case of short circuit on the board	Electronic protection	Fire propagation
RMM10	Carry out a DFMEA[2] analysis on battery container internal short circuit in order to determine the type of short circuit from which the container should be protected	Analysis	Battery internal short circuit
RMM11	Conceive a design that minimises the risk of insulation failure	Design	Insulation failure
RMM12	Use electronic boards specifically designed to avoid corrosion	Design	Corrosion
RMM13	Disable the fire detection system before entering inside the container	Rule	Asphyxia

[2] DFMEA stands for *Design Failure Mode and Effects Analysis*.

	Description	Classification	Risk/Undesirable Event
RMM14	Establish a visual verification of the battery container during the production phase	Quality check	Cuts and other injuries (due to sharp or cutting objects)
RMM15	Find out, according to the empty space existing in the battery container, the air leak and the result of RMM01, the acceptability of the substances released in case or thermal runway, venting or leaking cell; Calculate the maximum number of cells below which the concentration of asphyxiating, toxic, carcinogenic and flammable substances is not hazardous	Calculation	Burnt and fire propagation (due to flammable substances)
RMM16	Depending of the result of the RMM15, the battery container size should be enough to create a sufficient air renewal and stay below the hazardous concentration of flammable substances threshold	Calculation	Burnt and fire propagation (due to flammable substances)
RMM17	The maintenance and installation operators have to be qualified, strictly follow the maintenance and installation protocols and wear IPE[3]	Rule	Intoxication, electrical shock and burnt (due to carcinogenic, toxic or asphyxiating substances release or high voltage or current)
RMM18	The battery container installation on customer site has to be done by qualified operators only	Rule	Electrical shock and burnt (due to high voltage or current)
RMM19	The battery container has to be equipped with a safety valve in order to avoid overpressure	Mechanical protection	High pressure
RMM20	Establish a visual inspection of the container once arrived on customer site	Quality check	Shock, metal projection and sharp or cutting object
RMM21	Install a shock sensor inside the battery container in order to see if the container has been submitted to any significant shock during transportation	Mechanical protection	Shock, metal projection and sharp or cutting object
RMM22	The storage site should be a safe place with restricted access to reduce the probability of shock occurrence	Storage instruction	Shock, metal projection and sharp or cutting object
RMM23	The place where the battery will be installed should have a restricted access	Rule	Shock, metal projection and sharp or cutting object
RMM24	The module transportation has to be done in a solid closed box with no direct or easy access	Transportation Instruction	Shock, metal projection and sharp or cutting object
RMM25	The temperature on the environment external to the battery system and modules must be lower than the maximum allowable	Storage instruction	High temperature
RMM26	During preventive maintenance the battery container gaskets have to be checked	Storage instruction	Vermin and other animals
RMM27	The modules should not be directly installed on the ground without adequate protection	Rule	Vermin and other animals
RMM28	Use a system inside the battery container to control the humidity level during transportation	Transportation Instruction	Humidity
RMM29	Perform field studies before the container installation, to avoid install it on areas subjected to flood	Field study	Flood
RMM30	Protect the metallic structure of the container against corrosion, e.g. using corrosion-proof paint	Design	Corrosion
RMM31	Follow the preventive maintenance plan for modules as spare part (do not recharge them after an over discharge)	Rule	Charge after an over discharge (modules in storage)
RMM32	Preventive maintenance actions to verify the battery container paint (scheduled according to the external environment characteristics)	Rule	External aggressions
RMM33	Protect each battery module and battery system metallic part against corrosion	Design	Corrosion
RMM34	During assembling phases (cells and modules) verify if each connection is correct	Verification	Short circuit
RMM35	Strictly follow the maintenance and user manuals	Maintenance and usage instructions	High voltage or current
RMM36	Use ESD[4] protection equipment during electronic board handling	Maintenance and installation instructions	Electrostatic energy
RMM37	Implement an electronic protection against cell overheat	Electronic protection	Cell overheat
RMM38	Implement an electronic protection against overcharge on cell (to stop charge/discharge if a cell reach the maximum voltage value)	Electronic protection	Cell overcharge
RMM39	Implement an electronic protection against cell charge after an over discharge	Electronic protection	Charge after an over discharge
RMM40	Implement on the battery an electronic protection against overheating on battery	Electronic protection	Overheat on battery
RMM41	Implement on the battery an electronic and electrical protection against short circuit and overload to avoid fires	Electronic/Electrical protection	Battery internal short circuit/overload
RMM42	Perform electromagnetic studies during assembling to minimize the damage from electromagnetic radiation	Analysis	Electromagnetic radiation
RMM43	Provide test results during cell voltage inversion at nominal discharge current (200A/module) in order to verify there is no dangerous phenomenon	Test	Cell inversion

Table 16 – List of the proposed RMM (risk mitigation measures)

[3] IPE stands for *Individual Protection Equipmen*t.
[4] ESD stands for *Electrostatic Discharge*.