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Battery Cell Qualification Process for Electric Vehicles

Introduction

Due to concerns about climate change and global warming, various industrial sectors are strongly focusing on carbon footprint reduction strategies. Transportation is a significant contributor to global greenhouse gas emissions. Within transportation, electrification is a feasible solution to reduce passenger vehicle emissions. . Because of this, many automotive companies have been transitioning from internal combustion engine (ICE) to electric vehicles (EV) development and production over the past few years. Governments in some countries are also issuing regulations and offering incentives for the purchase of EVs. Due to these and various other reasons, the electric vehicle adoption rate for both private and commercial applications has been increasing year-on-year.

The majority of the EVs manufactured and sold so far are based on lithium-ion battery technology. Incremental improvements to existing battery technologies reach the market every year, improving safety, performance/capacity, and other key factors of the battery product continuously. In the meantime,

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research and development continues on next-generation batteries, disruptively changing the battery industry. Recent developments, such as solid-state electrolytes, silicon anodes, and cobalt-free cathodes are among the variety of promising advancements within the industry. These new technologies are mostly developed within research institutes but also in battery conglomerates, technology start-ups, or end-product automotive original equipment manufacturers (OEMs).

Every new technology needs to be fundamentally developed and extensively tested to be eligible for integration into a new battery product for commercial applications.

This case study gives a basic overview of the main factors to be taken into consideration in the supplier-OEM qualification process and elaborates on each phase from initial sampling up to final production validation. Additionally, some key insights from industry players on the practical application of this process are showcased.

The following key questions will be answered in this case study:

1. How could the EV industry increase the speed of qualification to adopt innovative solutions quicker?
2. How could a standard of product safety be created in the industry without significantly complicating the qualification process?
3. Which possibilities do individual suppliers and EV manufacturers have to improve the qualification process efficiency?
4. How does this qualification process differ between different companies, markets and types of cell form factors?

About Qualification

Qualification [of a product] is the process that leads to the confirmation that the product fulfils its requirements to be used in its intended purpose.

Testing and qualification of a new battery may take anywhere between several months to several years depending on how much has been already developed and qualified before. Qualification may be done by the supplier,OEMs, or an independent testing facility. Generally, testing initially takes place in laboratories of research centres under shared responsibility, or development consortiums up to the moment that commercial interest in the product has been gained. Both a clear methodology and also a proper process of testing and qualification are necessary to occur along the full battery supply chain: from manufacturers to OEMs. Mostly the testing and qualification are described in international and regional standards and regulations. Several upcoming standards and regulations are in work and more are expected to arise in the next years to come.

Global Context: Qualification of Cells for Electric Vehicles

As the largest market for battery usage with the broadest potential damage, the qualification process for battery cells for Electric Vehicles (EV) is the focus of this case study. OEMs often look for the procurement of battery cells, as modules and pack development often occur in-house. Therefore, this qualification process is discussed on the level of battery cells for the intended usage of EVs.

Globally there are more than 10 large OEMs that develop, manufacture, and sell different models of electrical vehicles (EV) to consumers. Each car model has different features related to range, battery capacity, performance, autonomous features, etc. There are no two vehicle models that offer exactly the same features. Even among the same EV brands, the manufacturers have deals with different suppliers for cell supply and the vehicles use different chemistries and shapes of battery cells. Exhibits A and B show an overview of the most popular EV manufacturers with the number of units sold in 2021.

These EV manufacturers have deals with large cell suppliers and make the cells used in their EVs. Some of these manufacturers use different form factors of cylindrical battery cells and others use pouch cells for their battery system. These battery cells used have various dimensions which results in different capacities and performance. Manufacturers usually define the overall battery capacity usually in kWh and provide features like fast charging capability and mileage/kW as well as the number of charging/discharging cycles for a specific model. It is rare for manufacturers to disclose anything related to chemistry, operating voltage window, or state of charge/state of health for the battery cells used in a vehicle. Different EV manufacturers also follow their own internal qualification process.

Following are brief descriptions of the different formats of cells used and relative pros and cons:

- **Cylindrical** - It is one of the most available formats of cell in the market and has been used by EV manufacturers like Tesla. It can be of 21700 format or more recently format 4680. These are mainly used in battery modules because it is easier to weld, and the temperature can be controlled more effectively when compared to prismatic or pouch cells.
- **Pouch** - This type of cell is used in certain EV applications as well. These cells have high packing efficiency and flexibility in battery design. However, there are some issues like gas formation, increasing pressure within the cell, and swelling that could cause serious damage if not handled properly.
- **Blade** - The cell unit of the blade battery is designed based on prismatic form factor. Unlike a traditional prismatic cell, the length of the battery is long while the height and depth are short. The blade is an LFP chemistry-based cell made by BYD Auto. It has shown a very high level of safety when compared to NMC or NCA-based lithium-ion batteries.
- **Prismatic Cells** - These cells are typically rectangular, and they offer better layering of the electrodes which leads to higher capacities when compared to cylindrical cells.

Case Study Process

Cell qualification is a time-consuming process that requires attention to detail. Since there are many cell suppliers and many different cell models, standardised battery cell test and validation procedures (henceforth called qualification) are required before a product can be deemed eligible for commercial usage in end-products like EVs.

This case study provides insights on the cell qualification process by OEMs and cell/pack/battery system suppliers which could provide a better understanding of what factors and steps to take into consideration before using the cells in a final consumer product (See Exhibit C).

Out of scope of this case study: further components or parts of the sub-system e.g. the Battery Management System (BMS). The BMS is a relevant part of the whole system which contains the adequate hardware and algorithms in software to provide and control and ensure battery function including safety and other operation-related information. Even if BMS parameters are important for the cell qualification this warrants a separate discussion..

Based on several interviews and discussions with members from different OEMs and suppliers it is understood that the process of cell qualification for EVs has plenty of similarities among different companies.

The Qualification Process Viewed Holistically

The qualification process covers both (1) the full chain from the Procurement, R&D Research and Development, Manufacturing, After-Sales and commercial aspects of both the supplier(s) and OEM, and also (2) the full lifecycle from concept/early development up to the series. and The qualification process has the following goals:

- Testing the product for its characteristics e.g., performance but also its process including its stability and reliability
- Verifying the proper fulfilment of requirements and/or claims for the supplier organisation
- Ensuring that the development/installation/manufacturing of a certain technology into a product and its process under the given environment is done fitting to the requirements.

The qualification process typically covers:

- **Design Qualification/Design Verification (DQ/DV)** - providing evidence that the product meets the requirements/specifications and fulfils its intended performance and functionality. This is mostly performed by R&D.

- **Installation Qualification (IQ)** - providing the evidence that the product or component of a product has been delivered according to the manufacturer's specifications.
- **Operative Qualification (OQ)** - providing the verification that the product and/or its subsystems or components are operating as designed. It verifies that the functionality meets the manufacturer's operational specifications.
- **Process Qualification (PQ)** - providing verification that the product operates or continues to operate as specified by the manufacturer. Typically performed for the first release but also regularly throughout the lifecycle according to the final customer's requirements. This is mostly performed by the Quality Assurance area of the company.

The process for cell qualification is part of the procurement and supply process and starts with the customers' needs or requirements.
During cell qualification he following steps occur:

1. OEM receives customer requirements (out of Marketing) or standards/ regulations (out of R&D) or other.
2. The battery or system engineering team converts the customer requirements into required technical specifications and use cases
3. Product Management (with the purchasing team) identifies key potential cell makers suitable for the requirement sheet.
4. OEMs can choose to bring the supplier(s) to develop a customised cell suitable for the requirements or identify supplier(s) with existing products matching their specification (off-the-shelf solutions).
5. The supplier(s) provides samples of the (sub-)products and a data sheet/qualification report to validate that the product fits the specifications.
6. The OEM involves the R&D testing and Quality team to revalidate, and check if the product and hence the suppliers are meeting the requirements.
7. Loop back if results don't match.
8. Proceed with purchasing contract negotiation if results meet the OEMs requirements.

The above sequence, as visualised in Exhibit D, should lead to a selected supplier and qualified product. The specific process of qualification lies in steps 5 and 6, whereby the supplier and OEM aim to validate the product according to the set requirements. The requirements, as elaborated in the chapter on the OEM perspective, involve performance, safety, and environmental aspects as well the fulfilment of existing standards and regulations.

The qualification process is not a one or two-step process, as it will require an increasing number of cells and extending requirements to get to a fully qualified product. Exhibit G shows the general process for one of the studied OEMs.

The result of such a qualification process leads to the confirmation that an extensively tested new technology, tailored to the customer application, is ready for commercial production. This means after the final stage of a qualification process with positive results: the commercial series production can commence.

Without a proper testing and qualification process: risks of low performance, safety issues, and/or unstable production could possibly hinder a successful use phase, whereby the customer might encounter large negative consequences. The avoidance of the potential negative impacts like loss of image / high costs and the whole business being put into question makes it very clear how relevant this prevention step can be.

Qualification Requirements

The requirements of the testing and qualification process are often prescribed by the OEM. Different OEMs can also have different requirements for quality, performance, and endurance. Nevertheless, not enough standardization takes place. This makes it particularly difficult for newcomers to find out how to properly evaluate and compare the full result(s) - giving the main reason for this case study. In addition, there are different types of OEMs, ones that work directly with the cell supplier and others OEMs who make their own battery modules/packs working directly with customers. OEMs that work with cell suppliers design the cells in a customized way according to their needs. However, the OEMs that work with customers test various cells that will be used in their product.

Cell Qualification standards

There are many cell, module, and pack level battery testing standards and regulations that are widely followed in the industry. Since there are no common international regulations and standards. OEMs mostly offer products adhering to previously selected standards that are market-related and are then considered to follow the industry-wide best practices.

Other than legal requirements (as of now only the UN38.3), there are also many industry standards for traction batteries on cell, module, and pack levels. Those standards set demands on the performance of battery systems regarding electrical tests, mechanical tests, and environment tests. These are mostly described under the standards IEC, ISO, UL, and SAE. Examples are ISO 6469, IEC 61982, IEC 62133, IEC 62281, UL 1642, UL 2580, SAE J2929 etc. Refer to Exhibit E for an overview of some of these standards. An extensive development is expected in the next months and years to come.

Cell Qualification from a Supplier Perspective

Battery cells are mostly supplied to OEMs by cell suppliers for usage in their final product. The qualification of the cell is a precondition for the qualification of the final product (EV).

Cell Supplier

The qualification test plan of EVs of a cell supplier consists of comprehensive tests carried out initially on a cell or a small number of cells including testing some samples to destruction. In further stages, qualification also includes testing of finished modules, battery packs, and battery (sub-)systems up to the complete EV itself.

How the testing plan is made: the testing for the qualification and its acceptance criteria primarily depend on the following main factors, as described in the worldwide and regional standards:

- Intended use of the battery cell
- Countries where production and sales are intended to occur (e.g., EU, UK, Japan, USA, China, …) - as this defines the standards that must be complied with and certification authorities that must be engaged..

- Different operating environments (e.g. hot/com, dry/humid)Chemistry / electrolyte type (e.g., Lithium, Nickel) - since standards are specific to battery chemistries
- Need for flight transportation - if flight transportation is needed then UN 38.3 certification is needed.Cell formats (e.g. cylindrical, prismatic, pouch, etc.)

Typically, the products for testing within the qualification process stages are named “samples”.

Like other components: also, the cell qualification has the sample naming such as Sample A, Sample B, etc. denoting which stage of the maturity phase the sample cells come from.

Sometimes, the cell suppliers might provide the samples to the OEMs starting from a very early stage in the qualification process based on their agreement/ responsibilities split. During this early phase, the cell supplier and the OEM might have only limited internal testing and would get support from the OEMs and/or from external labs for additional testing based on their use cases and responsibilities split. The cell suppliers can then optimise the cells within the early development phase based on such pre-testing results targeted toward specific OEMs' needs. Exhibit F is a table [3] that shows the sample category, description, and use, as communicated in the investor presentation of battery cell innovator Solid Power.

Depending on the requirements and the need of the OEM, typically the cell suppliers start sending samples from (pre-)A-Sample. Typically, the 5th stage D-Sample is the production-grade cells but sometimes more sample stages can be defined depending on various factors.

Once the sample reaches the C or D category, the OEMs generally perform large-scale testing based on different operating conditions, temperature, safety, and drive-cycle-profile. The testing verifies that the specific standards and requirements for the battery system / full product are met before being used in the series EVs. Such steps are discussed in detail in the below sections.

Some of the key roles and necessities of the cell suppliers are as follows:

- Developing new technology
- In-house testing
- Create prototype/sample product for commercial qualification processes
- Willingness to know the OEM requirements as early as possible
- Clear perspective through the qualification process results in a more reliable process and product

Qualification and Testing from the OEM Perspective

OEMs follow their own internal cell qualification process which typically last between some weeks/months to a few years. EVs usually have battery packs combined called a system. A battery pack is a collection of battery modules based on certain requirements. Battery modules are a discrete group of cells connected in series or parallel configuration(s) to achieve the desired voltage, capacity, and weight specifications.

Module Production Testing

Modules are usually made as an intermediate step and validated and qualified to assist manufacturing and assembly of the packs. This can be considered as sub-system level verification which includes thermal-related tests, vibration tests, drop tests and performance tests, etc. These tests provide insights into the quality of the product before combining them to make battery packs.

Exhibit G is a flowchart of the battery cell test qualification process from one of the OEM manufacturers. Exhibit H is an overview of reliability evaluation aspects for battery cells and packs [4]. This is an example of a Li-ion battery, and it can be applicable to several other chemistries. Description of the tests and regulations are provided in Exhibit I.

Environmental Qualification Tests

Batteries are sensitive to temperature and humidity changes. For instance, batteries can dry out quickly in a dry climate, and in high humid weather, can absorb moisture which can lead to shorter validity and leakage. Following are some of the standard environmental qualification tests.

- Temperature shock test (Thermal shock test)
- Damp heat humidity test

Safety Tests

There are three main categories of safety tests: UN 38.3, Certification, and Developmental Verification (DV). Each of these categories has different types of tests. All these tests are typically performed by the OEMs for the cell qualification process.

UN 38.3 Tests

These tests are required for a battery product to be transported by flight. It is required for all lithium batteries according to Section 38.3 of the United Nations Manual of Tests and Criteria: Lithium Battery Testing Requirements. Following are tests under UN 38.3.

- External short circuit test
- Overcharge test
- Forced discharge test

Certification Tests - Country Dependent

There are some certifications that are country specific.For countries that require additional certification: a valid certificate is necessary before selling the product in those countries. Some examples of the country-specific testing requirement(s) for batteries or modules are as follows:

- Overcharging control of current test
- Overheating control test
- Edge or corner drop test

Developmental Verification

There are multiple tests in this category which determine the reliable performance of the battery in the field when used in EVs. Developmental verification tests include:

- Insulation resistance
- Vibration

- Shock testing
- Extrusion
- IPX7 and IP6X
- General performance / electrical tests - see below

Performance / Electrical

Electrical tests comprise battery cell behaviour and performance-related tests under various operating conditions. This type of testing is critical because the results comprise most of what is required for cell qualification. These results also aid in any design changes required before designing the modules/packs. Following behaviour tests are the electrical tests, also required for cell qualification. The tests include:

- High altitude test
- Over-temperature protection
- Capacity and energy
- Energy efficiency
- Charging validation
- Heat dissipation
- High-temperature performance

Key Insights

According to regulations, standards and best practices, there are many similarities within the qualification process for cells of different form factors/shapes (cylindrical/ pouch/ prismatic/ blade). The standards are not different but only some testing and validation criteria differ.

Different OEMs who manufacture and/or use the cells in an end-product undergo mostly the same tests that are discussed in the earlier sections. Moreover, there are benefits of using one format of the cell over the other due to the pros and cons related to specific applications. Overall based on our discussions with different OEMs and available sources, the qualification process seems to be quite similar across different OEMs even if different standards may require different types or amounts of tests and cell samples to be tested and also different validation criteria.

Ashmore testing is invested into qualifications, this creates a greater sunk cost should the design need to be changed at a later stage. Cell development, including the qualification in full extent, can in some cases take up to five years. During this time there might come new developments that improve performance, safety, etc. A change from what has been qualified ends up being a very expensive and time consuming process. How much would need to be additionally tested to change what was already qualified? This is a big dilemma in the already expensive qualification process.

Conclusions and Outlook

The qualification process for cells involves the whole value chain from the cell supplier to the OEMs. There are various requirements that need to be satisfied. OEMs also need to follow certain standards, regulations and/or certification requirements (depending on the intended market) for which tests are conducted extensively. This paper also shows what is usually being tested regarding the methods and processes.

The requirements that are being tested in each round do not greatly differ. The major criteria being tested are performance, endurance, safety and environmental conditions - to ensure the final product meets the set requirements. What differes is which stakeholder is conducting the testing: the R&D team, the customer,, the manufacturing and/or the certification authority.

There are no substantive differences between the qualification process within the different companies analysed. The small differences found stem from matters such as company culture, budgetary constraints, and/or the strategy/vision and current priorities of the company. These factors see different companies place different levels of importance on quality, reliability and using the latest technology. and establish priorities on different aspect

The different types of cell forms are mainly tested in the same way. The form factor can nevertheless have special requirements (e.g. bending for pouch cells because of cell housing material).. Some housing might be more vulnerable and might need more testing.

The strongest dilemma for evolution in this field: Although a similar qualification process occurs, with recurring requirements and process steps, this is not necessarily an optimised process. The speed of the qualification process, cost of the materials/samples and its testing, and the quality-level of the products seem to have conflicting variables requiring a TRADE-OFF within the affected companies. Qualification rounds with tens of thousands of cell-samples for testing purposes only, or procurement cycles of five or more years till commercialisation can be achieved. During the period of one full qualification in the EV industry, other much faster competitors could have evaluated and optimised their state-of-the-art multiple times. This and other factors strongly related to the qualification are making it a real challenge for promising start-ups to enter the market with their emerging technologies.

The following key questions will be answered in this case study:

- How could the EV industry increase the speed of qualification to adopt innovative solutions quicker?
- How could a standard of product safety be created in the industry without significantly complicating the qualification process?
- Which possibilities do individual suppliers and EV manufacturers have to improve the qualification process efficiency?
- How does this qualification process differ between different companies, markets and types of cell form factors?

References/Bibliography

[1] Source: https://www.ev-volumes.com/

[2] Source Link: https://history-computer.com/largest-ev-companies-in-the-world/

[3] Solid Power, Investor Deck: A new breed of battery, June 2021

[4] Gandoman, F.H.; Ahmed, E.M.; Ali, Z.M.; Berecibar, M.; Zobaa, A.F.; Abdel Aleem, S.H.E. Reliability Evaluation of Lithium-Ion Batteries for E-Mobility Applications from Practical and Technical Perspectives: A Case Study. Sustainability 2021, 13, 11688. https://doi.org/10.3390/ su132111688

[5] https://www.espec.co.jp/english/products/trustee/test/short.html

[6] tuvsud-lithium-battery-testing-under-un-dot-38-3

Exhibits

Exhibit A: Chart of PEV, BEV, and EV market share between 2012 - 2021 [1]

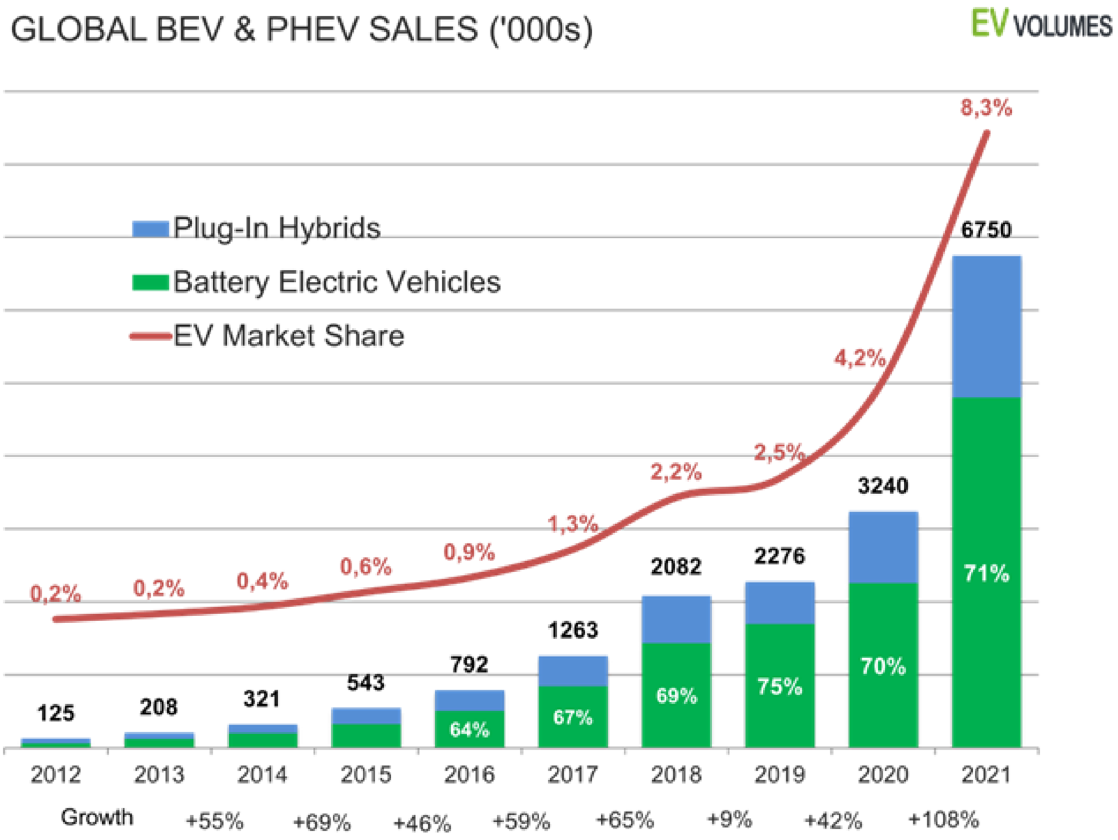


Exhibit B: EV Manufacturer & units sold in 2021 - worldwide [2]

EV Manufacturer	Units sold 2021
Tesla, Inc.	936,172
Toyota	674,450
BYD	593,743
General Motors	516,600
Volkswagen Group	452,900
BMW	328,316
Nissan	184,033
Hyundai	160,000
Ford	27,000
NIO	25,000

Exhibit C: Qualification of cell is necessary for qualification of end-product (full system)

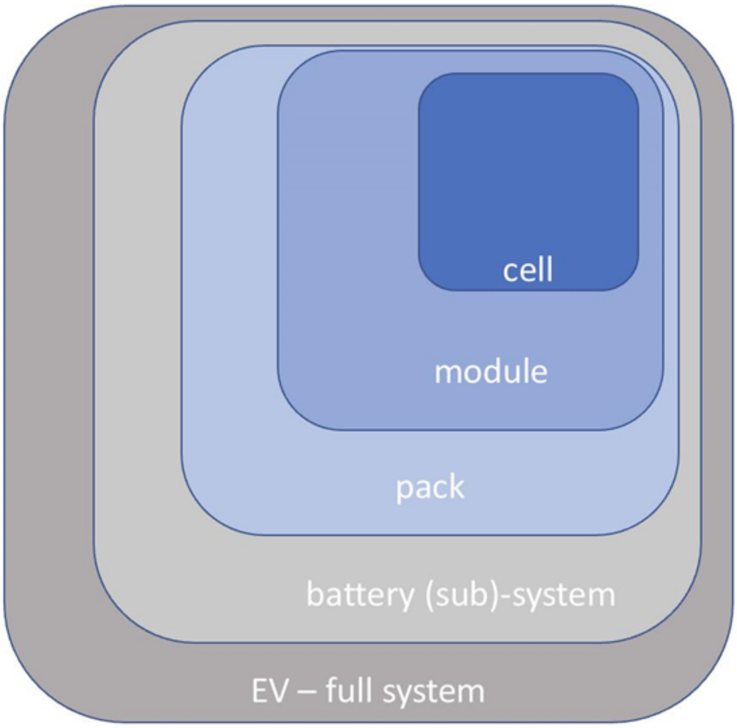
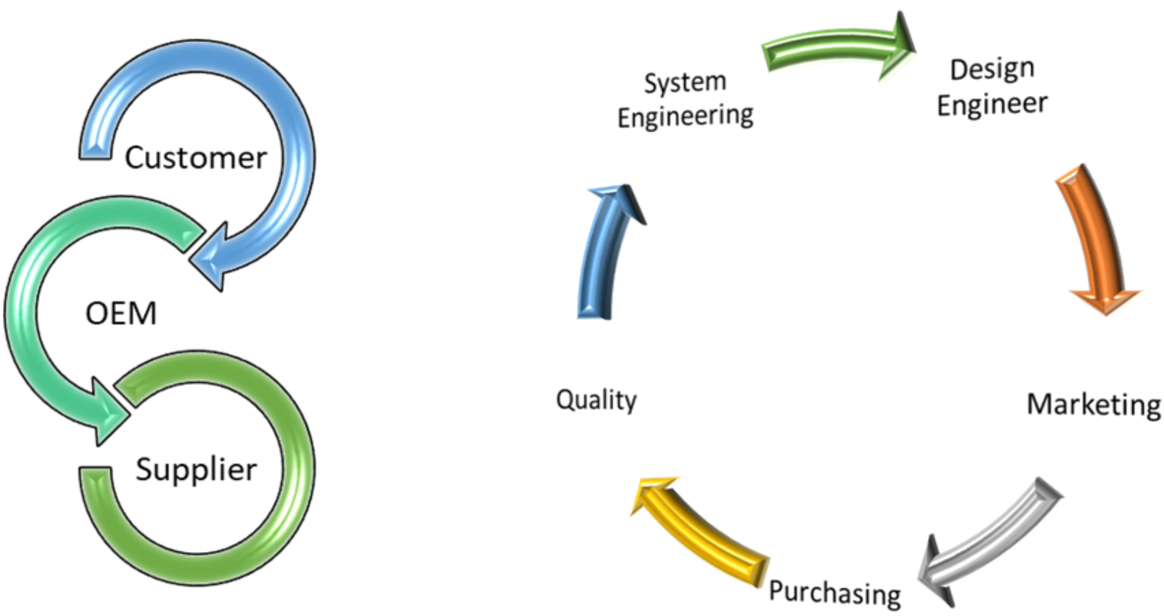
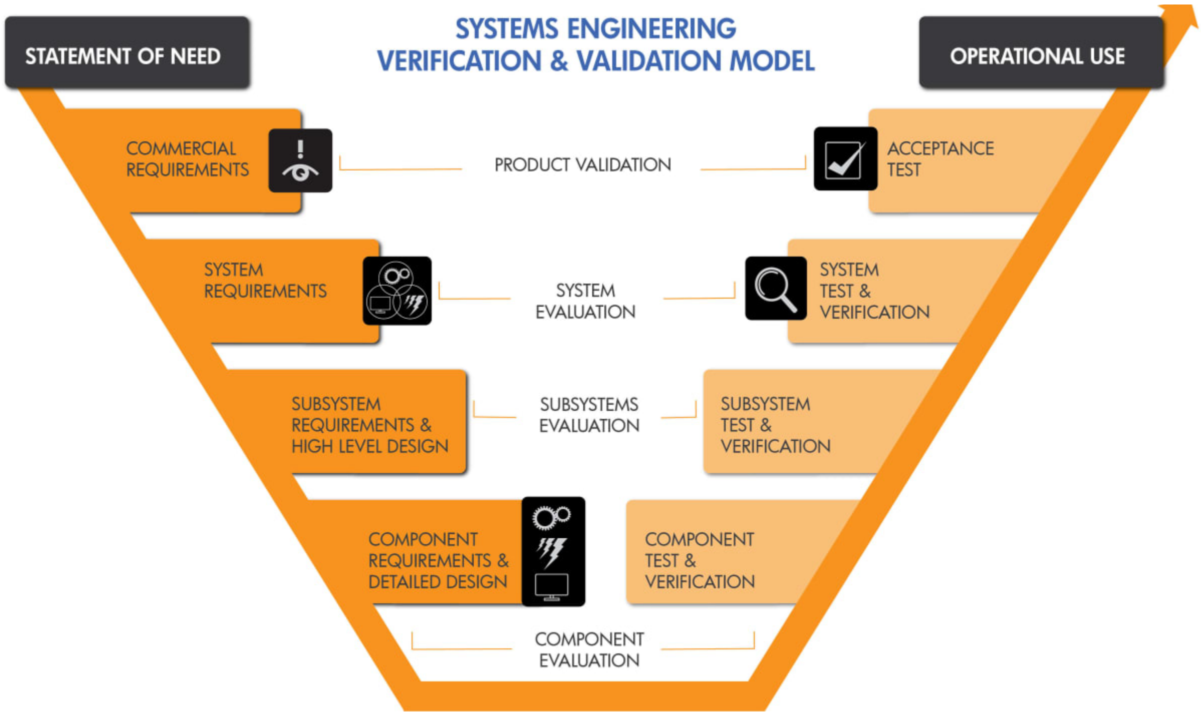


Exhibit D: Flow-chart of cell qualification





Systems Engineering Model (or V model) - Source: Sigma Technologies. The upper part is related to the OEM, the lower part related to the supplier (cell supplier), the right side of the V shows the qualification part of the process.

Exhibit E: Common standards/regulations for cell, module and pack testing

Standards /Regulations	Qualification Levels		
	Cell	Module	Pack
SAE J2464	Yes	Yes	Yes
ISO 12405-3	No	No	Yes
IEC 62660-2	Yes	No	No
Freedom CAR	Yes	Yes	Yes
SAND 2017-6925	Yes	Yes	Yes
GB/T 31485-2015:2015	Yes	Yes	Yes
UN/ECE-R100	No	Yes	Yes
GTR 20	No	Yes	Yes

Exhibit F: Sample Qualification Rounds within Solid Power [3]

Category	Description	Use
Pre-A Sample	Proof of concept	Proof of concepts or functions to ensure basic requirements as a product or process
A-Sample	Cell Concept Validation (CV) based on customer requirements	Probe multiple designs and material combinations to test performa against customer requirements
B-Sample	Cell Design Validation (DV)	Cell materials and design are frozen and the sample performance n customer specifications
C-Sample	Cell Process Validation (PV)	Final design (B-Sample) manufactured on production tooling and c meets customer specifications
D-Sample	Production Validation (PV+)	Full cell production at rate with needed quality and process certific

Exhibit G: Battery Cell Test Qualification Process from OEM A

(Note: CE valid only for Europe should be substituted for "certification in general" - if UK then UKCA, if China then CQC)

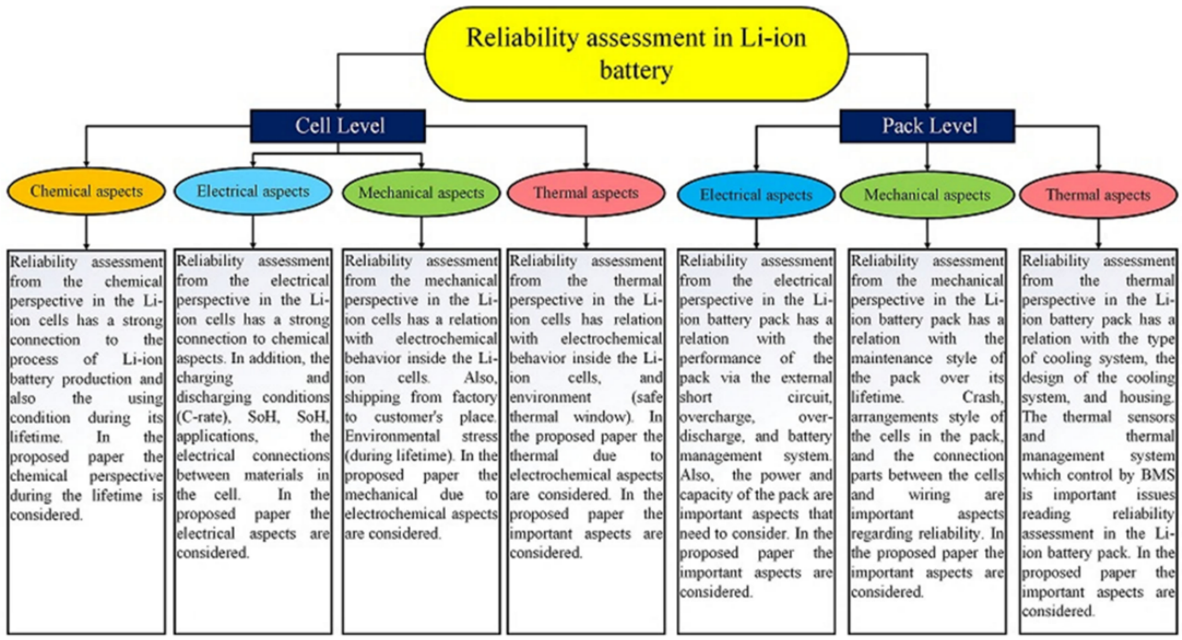
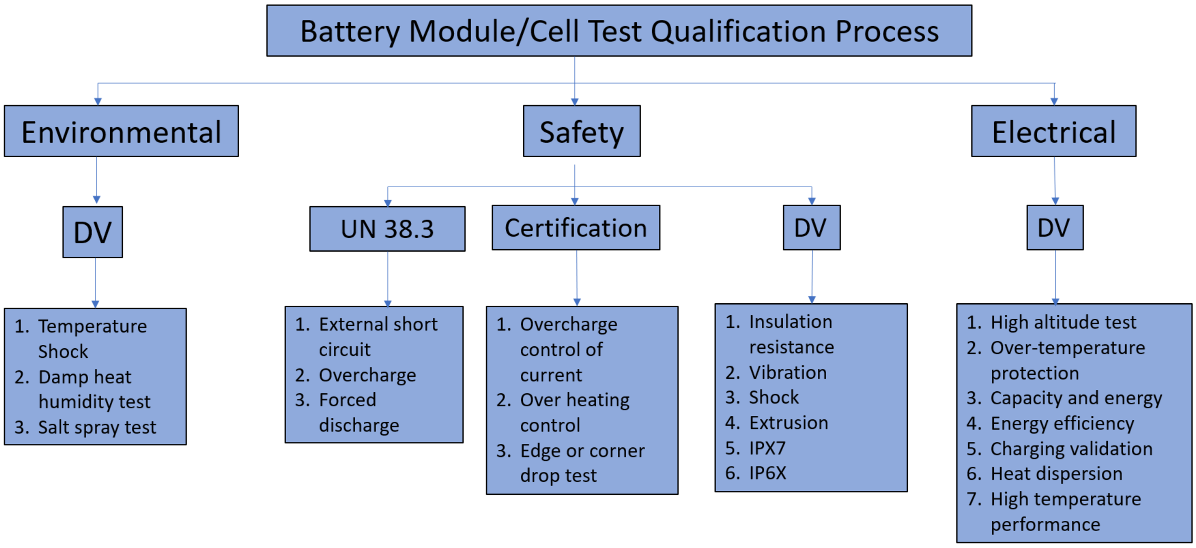


Exhibit H: Reliability Evaluation Aspects for Battery Cells



Flow-diagram of process of one of the OEMs

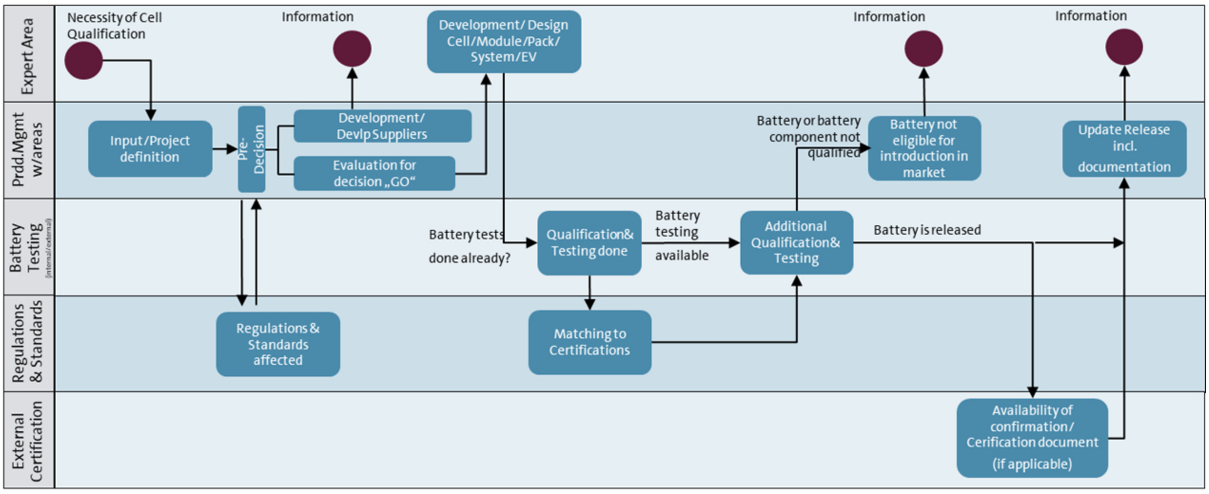


Exhibit I: Description of tests

Most of the tests are described in dedicated IEC, ISO, UL and SAE standards.

The standards describe generally the test procedure and parameters, the sample type and their amount and also the acceptance criteria.

Environmental Qualification Tests

Batteries are sensitive to temperature and humidity and their changes. For instance, batteries can dry out quickly in a dry climate and in high humid weather, they can absorb moisture which can lead to shorter validity and leakage.

a) Temperature shock test (Thermal shock test):

Temperature cycling and thermal shock chambers are suited for testing battery reliability under extreme temperature changes. Batteries need to be able to withstand drastic changes in temperature. Several thermal shock and temperature cycling tests are called out in the IEC, UL, and SAE standards:

- IEC 62133 - Temp cycling: 75 to 20 to -20°C (30 min. transitions)
- UL 2054 - Temp cycling: 70 to -40 °C (30 min. transitions)
- UL 1642 - Temp cycling: 70 to 20 to -40 °C (30 min. transitions)
- SAE J2464 - Thermal shock test: 70 to -40°C (15 min. transitions)

b) Damp heat humidity test

The humidity Test Chamber is made using reputed components having a long validity period. Two standard-sized trays are placed in the chamber for sample placement. The Temperature ranges from – 40 to +150°C and the Relative Humidity ranges from 20% to 98%RH.

Safety Tests

According to the application, the standards are to be chosen differently. In the case of automotive the most common are ISO 26262 (automotive safety in general) and also the ISO 62619 (battery safety in specific). There are also 3 main categories of safety tests described in UN 38.3, DV and Certification Testing. Each of these categories has different types of tests. All these tests are typically performed by the OEMs for the EV qualification process, containing the cell qualification as a pre-condition.

UN 38.3 Tests

These tests are required for a battery product to be transported either by flight or land /sea. It is required for all lithium batteries according to Section 38.3 of the United Nations Manual of Tests and Criteria: Lithium Battery Regulatory Requirements.

a) External short circuit test

External short circuit tests simulate incorrect battery usage. These tests consist of short-circuiting a battery from outside to simulate use that may cause fire or rupture. The battery's positive and negative terminals are connected to an external resistor, and the battery is observed to check for fire or rupturing. [5]

a) Overcharge test

The Overcharge test evaluates the ability of a rechargeable cell or battery to withstand an overcharge condition without adverse consequences. During the test, a sample is subjected to a current charge equal to twice that of the manufacturer's maximum recommended continuous charge current at ambient temperature for a period of 24 hours. To pass this test, the sample must not disassemble or ignite during the test, or within the seven-day period following the test. [6]

Forced discharge test

The forced discharge test assesses the ability of a cell or battery to withstand a forced discharge condition. During the test, a sample is forced to be discharged at ambient temperature at an initial current equal to the maximum discharge current specified by the manufacturer and for a calculated time interval. To pass the test, the sample must not disassemble or ignite during the test, or within the seven-day period following the test. [6]

Certification Tests (Certification Relevance)

The certification is country-dependent - while in Europe EC is required other countries require further certifications e.g., UKCA in the UK, CQC in China, etc. The required tests are like the ones that are described in the other chapters.

Examples:

Overcharge control of current test

Overheating control test / Thermal runaway test

Edge or corner drop test

Developmental Verification (DV)

There are multiple tests in this category, and they are essential for the product to have a reliable performance in the field when used in EVs.

a) Insulation Resistance

Insulation resistance is an electrical test that measures the condition of the insulation between two conductive parts and can be checked and tested once the product / sub-product is manufactured. It includes determining the voltage of the battery (one pole and then the other pole with respect to a grounding reference). Insulation resistance is measured in Ohm. An infinite resistance would be the perfect result, but no insulator is perfect so the higher the reading the better.

The insulation resistance measurement serves as an important test for detecting defects on lithium-ion battery cell production lines too. Structurally, this test is necessary to ensure that the components are properly isolated - since insufficient insulation resistance could lead to a risk of ignition or fire accidents.

This testing is important to be performed as a regular process check since insulation defects can be caused by battery cell production process weaknesses that can potentially lead to internal short circuits.

b) Vibration

The vibration test simulates the effect of the kind of vibration that could be applied to a cell or battery during transport and/or operation. During the test, the samples are shaken by a vibration machine and subjected to vibrations of varying amplitudes (dependent upon the size and weight of the sample being tested) typically over a three-hour period in each of three mutually perpendicular mounting positions. To pass this test, the sample must not leak, vent, disassemble, rupture, or ignite. In addition, upon completion of testing of a cell in its third perpendicular mounting position, the open circuit voltage of the tested sample must be at least 90% of the sample's voltage as measured immediately prior to this procedure. [6]

c) Shock

The shock test is intended to assess the robustness of cells or batteries

against cumulative shocks, such as those that might be encountered during transport. During the test, a sample is secured to a testing device and subjected to three calibrated shocks of varying intensity (again, depending upon the size and weight of the sample being tested) in both a positive and negative direction in each of three different mounting positions, for a total of 18 separate shocks. To pass this test, the sample must not leak, vent, disassemble, rupture, or ignite. In addition, the open circuit voltage of the tested sample must be at least 90% of the sample's voltage as measured before the test. [6]

d) Extrusion and Acupuncture Test

This test simulates a large plastic deformation that can happen in a crash condition, by either deforming or fracturing the material. A battery is only extruded/squeezed or peaked by a needle under certain test parameters described in the standards once and the battery is qualified if it does not explode or fire.

e) IPX7 and IP6X

These IPxx tests are related to an internationally recognized rating sealing exposure protection for dust and water/other fluids, most often tested at pack-level. In general, the withstanding of up to 30 minutes of submersions in water up to 40 inches (1 metre in depth) or similar.

Electrical

Electrical tests comprise the battery cell behaviour and performance-related tests under various operating conditions. This type of test is critical because this contributes to most of the results that are required for cell qualification. These results also aid in any design changes required before making the modules/packs.

a) High altitude test

Also known as the low-pressure test, the altitude simulation test simulates the operation and transportation of cells and batteries under low-pressure conditions, such as those experienced in an aircraft cargo hold, or in an aircraft cabin that experiences a sudden loss of pressure. During the test, a sample is stored at a specified pressure and at ambient temperature for at least six hours. To pass this test, the sample must not leak, vent, disassemble, rupture, or ignite. In addition, the open circuit voltage of the tested sample must be at least 90% of the sample's voltage as measured before the test. [6]

b) Over-temperature protection and Thermal Runaway

These battery heat tests are well described by IEC, UL, and SAE standards and are performed in special ovens equipped with special safety features.

c) Capacity and energy

There are various cycle-related, calendar capacity/energy tests performed on the cells. This includes testing the cells in different voltage windows, various current values, and drive-cycle tests. These tests are performed to qualify the cell performance.

d) Energy efficiency

Cycle tests are conducted to obtain the charge to discharge efficiency. If the beginning of life efficiency is lower due to certain reasons of the cells, then those cells may not be used in the final product.

e) Charging validation

There are different types of charging mechanisms. Some cells can sustain faster charging than others. However, most cells go through a standard charging procedure like constant current constant voltage charge without violating the safety limits. This ensures the validation of the cell's behaviour during charging protocols.

f) Heat dissipation

There are specific tests conducted at the cell level to measure the heat dissipated during the different tests. If the heat dissipation is high or results in safety issues the cells will not be used in the product.

g) High-temperature performance

OEMs typically manufacture different cells and cell models. There are variations in the chemistry, capacity, and format of the cells. Therefore, for EVs which will be used in a wide variety of temperature conditions, it is important to test the cells at different temperatures. One of the qualification tests would be testing the cell at a higher operating temperature for measuring the overall performance. This will be typically over 40 deg C. This is one of the tests that will determine the quality of the cell for specific applications.