DNV GL Handbook for Maritime and Offshore Battery Systems

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Table 0-1 Project team developing the previous Battery Guideline into a Battery Handbook

The Battery Handbook has been subject to a limited external review process. Separate review meetings (based on an early version of the Handbook) were held with FFI and NMD. The contribution and input from Øistein Hasvold, Torleif Lian, Sissel Forseth and Nils-J. Storkersen (all FFI) are gratefully acknowledged.

EXECUTIVE SUMMARY

Lithium-ion batteries are a disruptive technology that will significantly alter a variety of industry sectors including consumer electronics, energy, oil & gas and transportation - maritime included. Electric and hybrid vessels with energy storage in large Lithium-ion batteries and optimized power control can contribute to reducing both fuel consumption and emissions. Battery solutions can also result in reduced maintenance and improved ship responsiveness, regularity, resiliency, operational performance and safety in critical situations. A maritime battery might be up to several hundred times larger than a traditional electric vehicle battery. The high energy content, combined with extreme charging and operational patterns, represents new challenges in relation to safety, integration and service life. To avoid accidents and unwanted incidents that may have significant safety and cost implications – and potentially halt the development of these technologies – it is important that the battery related systems are verified and validated according to "best practice". This is particularly vital in light of unwanted events like – the explosion of a maritime battery system under test in Sweden and the 2016 recall of the Samsung Galaxy smart phone from the market. Battery safety has become a primary concern and potential competitive differentiator for all stake holders of battery powered and hybrid ships.

The aim of this Handbook is to help ship owners, designers, yards, system- and battery vendors and third parties in the process of feasibility study, outline specification, design, procurement, fabrication, installation, operation and maintenance of large Lithium-ion based battery systems (i. e. larger than 50 kWh). The Handbook is aligned with the DNV GL class rules for battery power at the time of publication.

DNV GL has cooperated with ZEM (Zero Emission Mobility) and Grenland Energy (GRE) to develop the previous Battery Guideline into a more comprehensive Handbook for safe and effective introduction of large maritime and offshore battery systems. In addition to addressing safety risks, the Handbook addresses economic risks such as failure of the business case due to improper selection of the battery system.

The main objective has been to improve the systematics, tools and criteria for safe and efficient introduction of lithium-ion battery technology. Target applications include hybrid offshore vessels and all-electric ferries and passenger ships. However, the Handbook is also valid for mobile offshore units and most ship types where Lithium-ion based battery power in all-electric and in hybrid configurations are being considered.

DNV GL’s Technology Qualification (TQ) process, was utilised to develop the previous guideline that is the basis for this Handbook. Technology Qualifcation has proven to be effective to identify and address challenges and weaknesses at an early stage in the realization of new technology. It is a risk based approach, focusing on the “vital few” when uncertainty is removed in a systematic way. A main aim of this Handbook is to reduce barriers and contribute to faster and safer battery electrification in the maritime sector.

Disclaimer

Table of contents

1 INTRODUCTION TO THE HANDBOOK

This Handbook provides an introduction to batteries and battery systems and provides guidance to ship owners, designers, yards, system- and battery vendors and third parties in the process of specification, design, procurement, fabrication, installation, operation and maintenance of large Lithium-ion based battery systems (i. e. larger than 50 kWh).

The Handbook is consistent with the October 2015 release of the DNV GL rules for battery power, but for classification purposes, the rules shall be used directly.

To avoid accidents and unwanted incidents that may have significant safety and cost implications, battery related systems need to be verified and validated according to "best practice". This Handbook aims to describe such a best practice providing recommendations for safe and effective introduction of large maritime battery systems with focus on potential applications in hybrid and all-electric vessels. In addition to addressing safety risks, the Handbook addresses economic risks such as failure of the business case due to improper selection or integration of the battery system.

The battery information and recommendations are presented separately for the different phases of the ship building process (Chapter 4 onwards). Relevant definitions and the generic system used as a basis for the system recommendations are described in Chapter 2.

1.1 Background

The commercial operations of the world's first fully electric powered car ferry started in 2015[1]. Since this time battery power has been increasingly adopted, proving to be one of the most transformative technologies introduced to the maritime sector. This progression is expected to continue as there are on-going technological developments in the battery sector. On short and medium sight, significant increase in cycle life, energy density and lower cost are expected, and technology continues to outperform market forecasts. The cost decrease has been partly due to increased manufacturing volumes, cost decreases in the supply chain and improved yield. On the technology aspects, significant improvements in energy density, which also lead to lower cost per kWh, are continually being realized. Additional cost reductions may accompany the entry of battery technologies into new markets. There have also been significant improvements in C-rates/power density, safety and cycle life.

Several projects have investigated battery electrification of various ship types showing that there is considerable potential to reduce both energy consumption and emissions of CO_2, NO_x and particulate matter. In addition to all-electric city-, car- and cargo-ferries for "shorter" distances, ideal ship types for battery hybridization typically have large variations in power demands, high redundancy requirements, and/or low utilization of the engine for long periods of time. Ship types of particular interest are ferries, offshore vessels, drill ships, shuttle tankers, wind farm vessels, icebreakers, passenger boats, fishing boats, tugs and other workboats and special ships with large load variations of the main or auxiliary machinery.

Low sulfur fuel requirements are expected to lead to a 30 – 50 % fuel cost increase over the next decade. In some countries and ports there will be local regulations pushing for reduction of local air pollution as well as use of shore electric power. Strict regulations, high fuel price and lower battery prices combined with the Energy Efficiency Design Index (EEDI) requirements and expected additional CO_2 and NOx regulations will lead to the development and use of novel technologies and fuels such as biofuel, hybrid propulsion systems and last but not least, cost effective and safe battery systems.

[1] http://www.ship-technology.com/projects/norled-zerocat-electric-powered-ferry/

All-electric ships and hybrid ships with energy storage in large batteries and optimized power control can give significant reductions in fuel costs, maintenance costs, emissions, as well as improved ship responsiveness, regularity, operational performance and safety in critical situations. Hybridization of ships may provide fuel savings of 10 - 40% and payback times as low as less than one year – specific results depend heavily on the conditions of each project. Technical feasibility and environmental benefit summaries can be found in Appendix E. Battery power support can improve performance of diesel fueled systems as well as LNG fueled systems, new building or retrofit, and it can work as a storage unit for energy from waste heat recovery, regenerative braking of cranes and renewable energy. It is a necessary component in hydrogen fuel cell systems. Hybrid and pure battery operation works well in conjunction with shore power and low carbon sailing in the port area, and it helps solve local emission problems. Long term it is expected that the charter and second-hand markets will pay increased premiums for fuel efficient ships. Due to an increasingly improved business case, improved technology and new regulations, more and more vessels are expected to be hybrid or plug-in hybrid.

1.1.1 DNV GL Class Rules

DNV Class published tentative rules for using Lithium batteries on-board vessels in 2012. These rules were updated and published in October 2015 under the common rule set of DNV GL. The requirements are function-based and applicable for all DNV GL classed vessels having batteries larger than 50 kWh. The rules primarily focus on the safety of the complete battery installation and the specific test requirements for such a system. In addition to the requirements, there are two class notations named Battery (Safety) and Battery (Power). The notation Battery (Safety) is mandatory for all DNV GL classed vessels where the installation is used as an additional source of power and has an aggregate capacity exceeding 50kWh. Battery (Power) is mandatory for vessels where the battery power is used as propulsion power during normal operation or when the battery is to be used as a redundant source of power for main and/or additional class notations.

Class rules for Battery notation can be found in Part 6, Chapter 2, Section 1 of the DNV GL Rules:

http://rules.dnvgl.com/docs/pdf/DNVGL/RU-SHIP/2016-07/DNVGL-RU-SHIP-Pt6Ch2.pdf

Type approval requirements for lithium ion batteries can be found as Type Approval CP 0418 for Lithium Ion Batteries:

https://rules.dnvgl.com/docs/pdf/DNVGL/CP/2015-12/DNVGL-CP-0418.pdf

The specific links provided above are valid as of December 2016, but in the case that updates have occurred, updated documents will be available under the same names.

2 DEFINITIONS AND ABBREVIATIONS

A60	Grade for fire proof walls and doors[2].
AC	Alternating Current
Battery space	Physical installation space including all functions and components which contribute to keep the battery system in this space within specified set of conditions (e.g. temperature etc)
Battery system	One or more battery strings including all required systems for the intended purpose
BMS	Battery Management System; designed by each vendor, BMS are complex control systems which provide balancing, monitoring and protective functions to the battery.
CID	Current Interrupt Device
Cell	The smallest electro-chemical unit
C-rate	The power or current used to charge or discharge a battery, normalized by its capacity. Such that, C-rate = current (amps) / capacity (amp-hours)
Cycle	A battery going from fully discharged, to fully charged, and then fully discharged again. Partial cycles, not going from full discharged or to fully charged, should be summed to correlate to full cycles as relevant.
DC	Direct Current
DOD	Depth of Discharge, or Delta State of Charge (DSOC), is the amount of SOC traversed during a given partial cycle
DUT	Device Under Test
E/E	Electric/Electronic
EMS	Energy Management System
EUC	Equipment Under Control
EV	Electric Vehicle
FMEA	Failure Mode Effects Analysis
FMECA	Failure Mode Effects and Criticality Analysis
Fire	Class A: Ordinary combustible materials, such as wood, cloth, paper, rubber and many plastics. Class B: Flammable liquids (burn at room temperature) and combustible liquids (require heat to ignite). Petroleum greases, tars, oils, oil-based paints, solvents, lacquers, alcohols, and flammable gases. Class C: Fuels that would be A or B except that they involve energized electrical equipment. Class D: Combustible metals, such as magnesium, titanium, zirconium, sodium, lithium and potassium. Class K: Fires in cooking appliances that involve combustible cooking media (vegetable or animal oils and fats).
H60	Grade for fire proof walls and doors[3].
HVIL	High Voltage Inter Lock
IAS	Integrated Automation System
ICE	Internal Combustion Engine
IP	Ingress Protection
LEL	Lower Explosive Limit, similar to Lower Flammability Limit, LFL
$LiCoO_2$	Cell chemistry: Lithium Cobalt Oxide

[2] A-rating means testing based on a normal ISO standard fire curve (cellulosic fire). The item should maintain specified insulation performance, integrity and load bearing capacity for 60 minutes.

[3] H-rating means testing based on a Hydrocarbon fire curve (i.e. higher temperatures than for A-rated items). The item should maintain specified insulation performance for 60 minutes, and integrity and load bearing capacity for 120 minutes.

$LiFePO_4$	Cell chemistry: Lithium Iron Phosphate
$LiFeO_4F$	Cell chemistry: Lithium Iron Phosphate Fluoride
$LiMnO_2$	Cell chemistry: Lithium Manganese Oxide
LiNMC	Cell chemistry: Lithium Nickel Manganese Cobalt Oxide
LTO	Cell chemistry: Lithium Titanate Oxide
Module	Assembly of cells including some level of electronic control. The smallest unit that can be electrically isolated.
MSDS	Material Safety Data Sheet
PCB	Printed Circuit Board
PE	Protective Earth
PMS	Power Management System
PSDS	Product Safety Data Sheet
RP	Recommended Practice
RT	Routine Test = conformity test made on each individual item during or after production
SDS	Safety Data Sheet
SIL	Safety Integrity Level
SOC	State of Charge in percentage of the rated capacity available for the discharge of the battery (fuel gauge)
SOH	State of Health. Reflects the general condition of the battery and the ability to deliver the specified performance compared to a new battery. This can refer to either energy capacity or internal resistance.
SOLAS	Safety Of Life At Sea
String	Smallest unit with same voltage as the system level
SWOT	Strength Weakness Opportunity Threat
TT	Type test = Conformity test made on one or more representative of the production
Thermal Runaway	A fire or combustion event where an increase in temperature causes further increase in temperature in a feedback loop. Also characterized as self-heating or exothermic. Sometimes quantitatively defined as self heating at a rate above 10°C/min.
RT	Routine test
UPS	Uninterruptable Power Supply

3 MARITIME BATTERY SYSTEMS AND HOW THEY WORK

A battery is an electrochemical system that can store electric power with very high responsiveness. This allows the operator the freedom to store unused or excessive energy and then utilize the energy when it would benefit the operation of the ship. With recent technological developments, the price of battery systems is reducing while performance is increasing, making them competitive in new market segments.

Compared to traditional batteries with water based electrolytes such as lead acid and nickel cadmium batteries, lithium-ion batteries can store between two and eight times more energy per weight unit. The high energy density as well as the use of a flammable electrolyte makes a safe design more challenging. Lithium based battery systems therefore depend on a well designed and tested electronic control system and physical design for safe operations.

This section will outline advantages, usage areas and the fundamentals related to battery systems.

3.1 Why use Batteries?

Battery systems can provide the flexibility and freedom to store electrical energy and utilize the energy when it is most beneficial for system operation. This is a benefit that has been proven by batteries in hybrid electric terrestrial vehicles. In a hybrid car, the battery can help smooth the load of the engine. Some battery systems are designed to provide high power with very high response rates which allows the engine to run steadily and more efficiently. When the vehicle is slowing down or is operating at less than its peak efficiency, the battery can be charged, storing energy for the next task. These same benefits translate directly to maritime propulsion systems – utilizing battery power to avoid inefficient regions of engine operation. Batteries can be used in a hybrid ship to avoid low load diesel conditions in port and thereby reduce emissions. The same batteries can then be used to reduce ramping and optimize loading between generator sets and increase system fuel efficiency, as well as reduce operating hours and maintenance. Additionally, batteries are capable of providing standby power for redundancy with zero fuel consumption penalties. Thus, not only are battery systems able to increase system efficiency, but also provide a means to increase system reliability and robustness.

Traditionally, batteries have not been utilized on a large scale in maritime and offshore applications. A reason has been that the specific power and energy density of the available batteries have not been able to meet the needs of such applications. Short life time expectations have also been a challenge. Lead-acid and Nickel Cadmium batteries with a very limited capacity compared to weight and size exist on many modern vessels today in different uninterruptible power supply and clean power applications. These are however not intended for continuous use in high power operation and are mostly installed as back up devices. The use of batteries is changing due to the emergence and maturation of new technologies such as lithium-ion batteries with a much higher energy density and cycleability than lead-acid or Nickel Cadmium batteries. Since the invention of the lithium-ion battery in the 1980s and the subsequent commercialization in the 1990s, the development was first driven by consumer electronics and later adopted by the automobile industry to also include higher power and energy applications. Figure 3.1 outlines some of the major milestones in the development and utilization of lithium-ion technology.

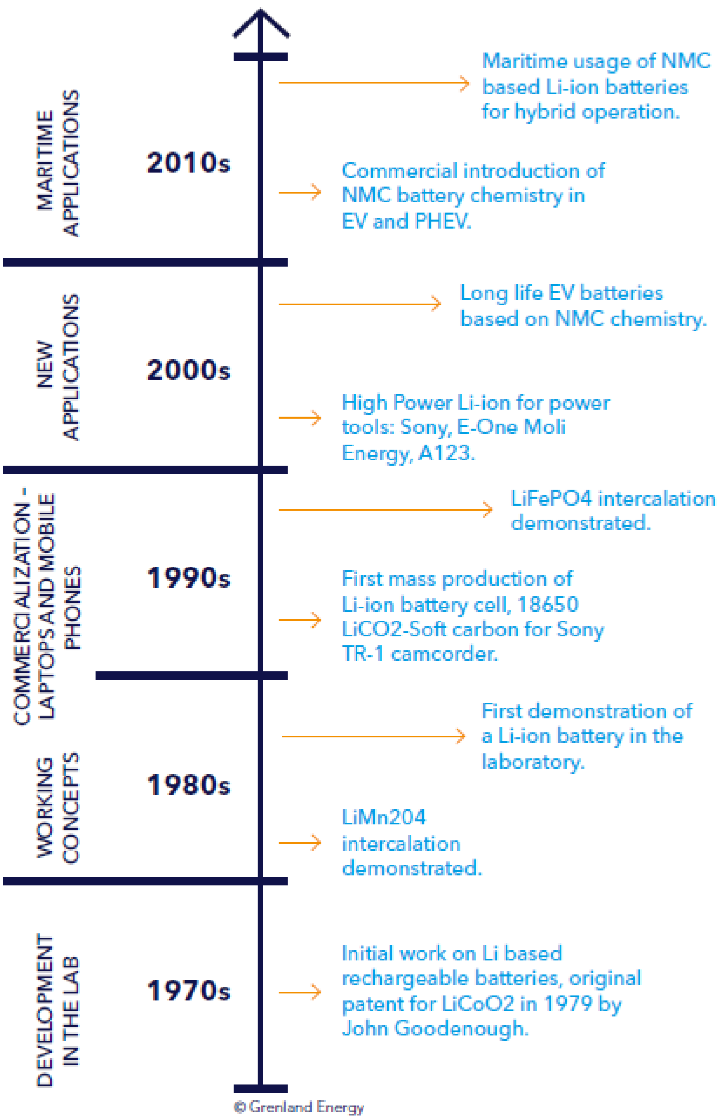

Figure 3.1 Milestones of lithium-ion battery technology

Figure 3.2 compares the specific power and energy for different battery chemistries. It shows that with the introduction of lithium-ion, applications which require high levels of both power and energy could utilize battery systems. Additionally, prices of lithium based cells and systems have significantly been reduced over the last years - these trends in price reduction continue to surpass market forecasts and are expected to continue in the years to come.

Maritime requirements also impact the cost of batteries intended for maritime usage. The main cost drivers compared to batteries intended for consumer electronics and electric vehicles are related to enhanced safety and performance requirements, more stringent life time requirements and increased system complexity. Installations for ships are commonly customized (when compared to automotive applications) and produced in lower volumes.

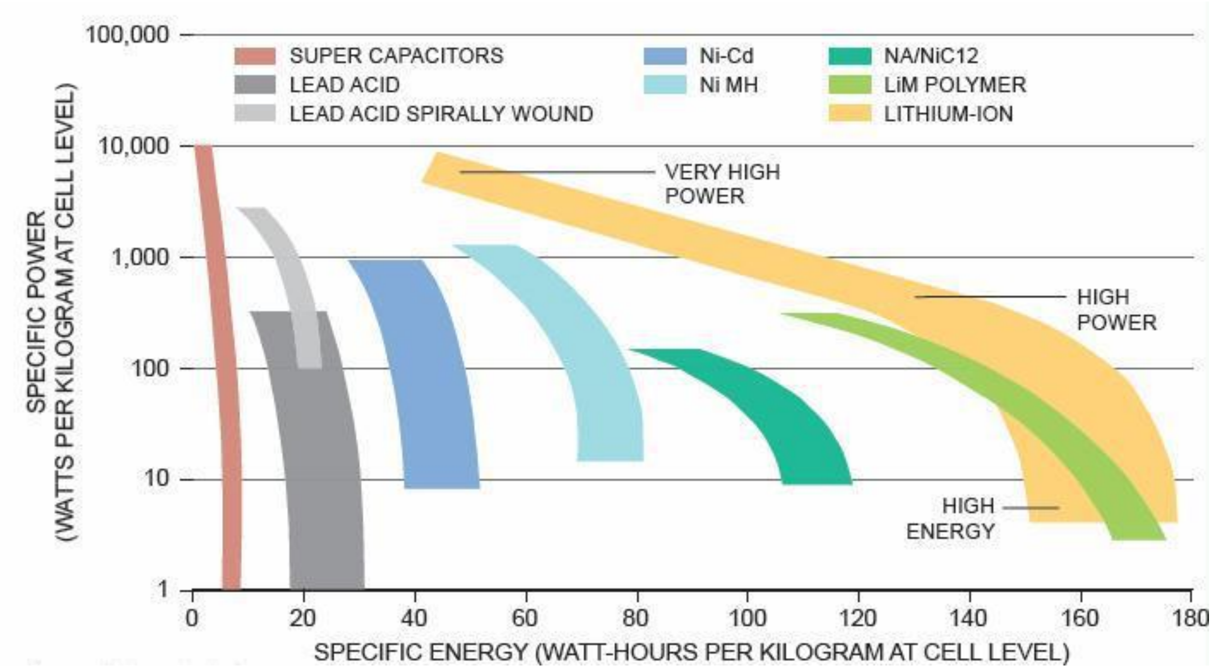

Figure 3.2 Specific power and specific energy of different battery chemistries (source Johnson Controls)

The benefits mentioned in this sub-chapter relate to both financial and environmental aspects and it is wise to carefully consider these when deciding whether or not a large battery installation is feasible for a specific project. Other aspects, such as risks and safety hazards related to the installation, also need to be evaluated. In order to fully understand these, it is important to understand the basic structure of a battery.

3.2 What is a battery?

A battery is an electrochemical device that stores electrical power through chemical reactions that are electrically driven. These reactions occur at the positive and negative terminals, called electrodes. When charging a lithium-ion battery, as illustrated in Figure 3.3, positively charged lithium ions travel through a separator from the positive electrode to the negative electrode. Once this electric potential is stored, in the form of lithium ions collected on the negative electrode, it can be utilized as electric energy by connecting a load between the terminals. In this way a battery can be charged using electrical energy when it is available in excess, and then utilize the battery's electrochemical desire to discharge in order to provide electricity when needed.

The term State of Charge (SOC) describes the energy available for use in the battery system as dependent on specific conditions (i.e. within a certain power range). A fully charged battery system has a SOC of 100% (most of the cycleable lithium ions located at the negative electrode), while a fully discharged battery system has a SOC of 0%. Determination of SOC is a complex calculation that depends on closely monitoring power (electron or current flow) in and out of the battery as well as voltage and temperature. However, these calculations must be calibrated specifically for a given battery cell type, are highly temperature dependent and must also factor in non-linear effects of different power levels and voltage or SOC ranges. The complicated nature of this calculation thus points to the need for a highly developed Battery Management System (BMS), as reviewed in Section 5.4.

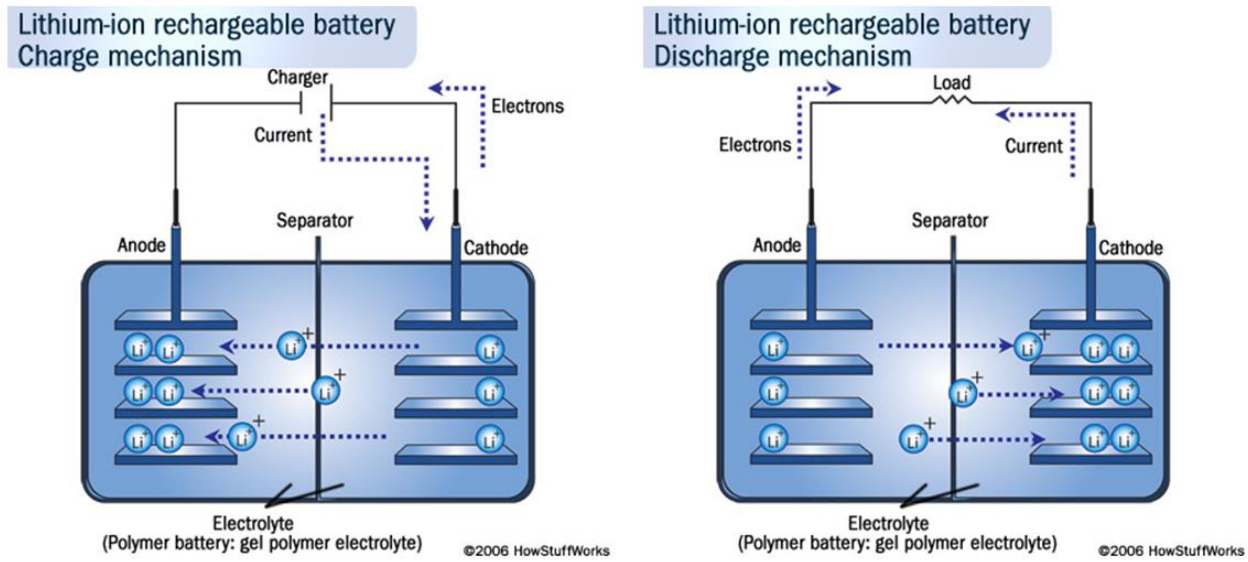

Figure 3.3 Basic principles and components of a lithium-ion battery

Lithium-ion batteries will unavoidably degrade with use. As the cell is charged and discharged repeatedly, the ability to accumulate ions at the negative electrode will gradually decrease. The State of Health (SOH) reflects the general condition of the battery and the ability to deliver the specified performance compared to a new battery. This primarily refers to a reduction in the total amount of energy that the battery can store or release, a reduced capacity; but for some applications reduction in power capability (due to increasing internal resistance) may be equally or even more important.

The traits of a battery, such as how much energy it can store or how fast it can charge or discharge, are dependent on the cell composition, which includes design parameters as well as chemistry. A battery can be based on a variety of commonly used lithium-ion chemistries which represent different battery characteristics. Maritime battery systems will typically be built of several thousands of cells, and as such it is vital that each cell operates consistently with all other cells. This requires both that the battery BMS is able to successfully control and operate each cell in a balanced manner, and equally that cells are manufactured of good and equal quality. Lesser quality batteries are available on the market as the result of cheaper production methods, but are associated with greater risk – of unwanted failures like shorter lifespan, inconsistent voltage, inconsistent capacity or in worst cases internal failures that can lead to fire.

Battery cells for maritime usage come in three main formats, cylindrical, large format prismatic and soft pouch. Some important characteristics of these three cell types are given in Table 3-1.

Property	**Cylindrical**	**Soft pouch**	**Prismatic**
Enclosure	Steel or aluminum	Multi-layer laminate pouch	Aluminum Plastic Steel
Cell vent mechanism	Fixed direction at specific pressure	Packaging failure vents at low pressure	Fixed direction at specific pressure
Mechanical current interrupt device (CID)	Can be included in header	Non existent	Can be included in header

Table 3-1 Characteristics of cell types, or form factors, applicable for maritime use

The table illustrates that each different battery cell form factor, or packaging approach, has a range of attributes or disadvantages as far as safety enhancing features. For the soft pouch cells, a cell explosion resulting from internal pressure is not possible because the soft pouch will tear at a relatively low pressure. The safety enhancing features that can be installed in cylindrical and large format prismatic cells include mechanical Current Interrupt Devices (CID) as well as more controlled venting in case of cell level abuse. This points to the importance of quality control on vent mechanism design and manufacturing.

If cell, module or system ventilation fails, flammable concentrations can build up and present an explosion risk. This is discussed in detail in Section 5.1.2.

3.2.1 Battery chemistries

Commercially available battery chemistries on the market today utilize largely similar elements. Anodes have historically been carbon or graphite based, while electrolytes predominantly consist of organic carbonates such as ethylene carbonate, dimethyl carbonate, diethyl carbonate and ethyl methyl carbonate. Some of the most promising developments for lithium-ion battery safety, energy density, and longevity may come from advancements in these areas. Component quality and manufacturing process will have a substantial effect on performance, longevity, consistency, and safety. Other key factors are the anode chemistry and material properties, the electrode active material coating thickness and porosity, the electrolyte, the separator, the current collectors and the cell construction. However, the chemical composition of the positive electrode (cathode) is one of the most defining aspects of a given battery's performance characteristics. This is the name that is commonly referred to in describing different battery technologies (LiFePO, NCM). This material composition is important for such factors as power and energy characteristics, lifetime, safety thresholds, voltage as well as cost. A few of the most common cathode chemistries are listed below. Cell compositions now also increasingly utilize a mixture of these different chemistries on the cathode.

- **Lithium cobalt oxide, $LiCoO_2$ (LCO) -** The main advantage of $LiCoO_2$ is its relatively high energy density. However it typically displays lower power (rate) capabilities and shorter cycle life. Impedance increase over time is also a significant concern with $LiCoO_2$ based cells. Cobalt oxide suffers from safety concerns due to the exothermic release of oxygen at elevated temperatures – producing a self-heating fire resulting in thermal runaway concerns. LCO type cells are very common in consumer electronics rechargeable batteries where a three year life span of a few hundred cycles to 80% of its original capacity often is sufficient.

- **Lithium manganese oxide spinel, $LiMn_2O_4$ (LMO) -** LMO is a somewhat unique cathode chemistry, being a spinel structure, which provides significant benefit in terms of power capabilities. The compound has additional safety benefits due to high thermal stability. However it has significantly lower energy capacity compared to cobalt based compounds, and is known to have a shorter cycle life characteristics especially at higher temperatures. Several material modification possibilities exist in order to improve the cycle life of LMO compounds.

- **Nickel manganese cobalt oxide, $LiNi_{1-x-y}Mn_xCo_yO_2$ (NCM or NMC) -** NCM is one of the most recent cathode developments and is the present market leader for large format applications and are starting to replace LCO as the dominant chemistry for consumer electronics. It's strength is the combination of attributes of the constituents of nickel (with a high specific energy), cobalt (high specific energy) and manganese (doped in the layered structure to stabilize it). The relative composition can be tweaked to produce different properties with regard to power density, energy density cost and safety, as well as customize the cells to certain applications or groups of applications. NCM can also be mechanically mixed with LCO or LMO in the cathode in order to produce yet another customization of properties.

- **Lithium iron phosphate. $LiFePO_4$ (LFP) -** Like LMO, LFP differs significantly from most other cathode chemistries in terms of its structure, which is phosphorous-olivine rather than a layered metal oxide. A dominant benefit of this is the lack of an oxygen source at the cathode, thus posing a potentially reduced risk magnitude during thermal runaway. These cells are additionally more resilient to temperature fluctuations. The specific energy of $LiFePO_4$ is relatively low, and the electrochemical potential (voltage) is lower, reducing the cell's driving force. Power capabilities of a $LiFePO_4$ based battery cell are inherently low; however, doping the $LiFePO_4$ material with small amounts of other materials, conductive coatings and nanostructured active material particles have enabled typically high power battery cells using $LiFePO_4$.

Another important characteristic of the different chemistries are at which voltage level they operate. With some chemistries, it is possible to obtain a higher voltage when fully charged, but with a rapidly decreasing profile as the SOC reduces. Figure 3.4 illustrates that there are significant differences when it comes to cell voltage. Of particular note, the flatness of the $LiFePO_4$ voltage can complicate controls and monitoring.

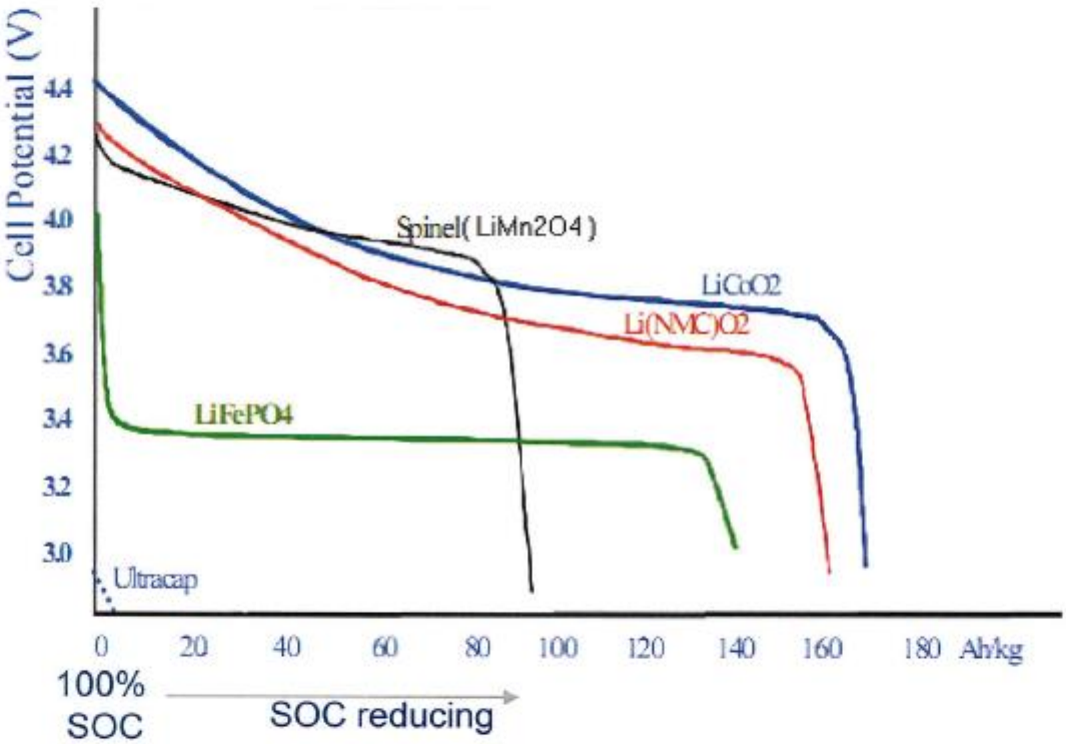

Figure 3.4 Cell voltage as a function of SOC is an important feature for controls and power production

In addition, many developments are presently taking place with new anode chemistries. Silicon is increasingly used along with carbon to increase the energy capacity. In addition, titanate is now being offered as an anode chemistry which has demonstrated positive benefits with regard to power capabilities, cycle life as well as temperature resiliency – identified in the market often as Lithium Titanate Oxide (LTO) cells. Along with advanced manufacturing processes and capabilities, the experimentation with new chemical combinations and components in lithium-ion batteries is producing continual benefits and advances, with new developments each year.

3.2.2 Degradation mechanisms

Lithium ion batteries will lose capacity and exhibit an increase in internal resistance over time. This degradation is due to the use of the batteries through cycling as well as calendar effects that will inevitably occur over time. Degradation due to both cycling and calendar effects is highly dependent on temperature. The higher the temperature the more rapidly the cell will degrade, with additional risks presented at low temperatures. The optimal cell temperature is often in the range from 20 – 30 °C, depending on chemistry and system design. Exposure to temperatures outside of the rated operating range poses significant risk of reduced lifespan. Reduced lifespan, or State of Health (SOH) must be accurately calculated and monitored by the system controls – typically referred to as Battery Management System (BMS). For example, lithium plating or dendrites can be formed if the battery is charged with a high current at low temperature. Lithium plating will irreversibly reduce the capacity of the battery. The extent of the irreversible capacity reduction depends on the detailed characteristics of the charging overcurrent /5/. Temperatures are thusly highly monitored and controlled for maritime battery applications, and thermal management is a key factor in system design. At the extremes, these aspects that cause accelerated degradation can also pose safety risks.

Figure 3.5 below shows a model output to illustrate the impacts of higher temperatures on the calendar component of degradation – showing that at a higher temperature the amount of useable capacity expected to remain after 5 or 10 years may be very low. In addition, studying calendar loss shows the detrimental effect of extended periods of time at higher SOC, as shown in the figure. Lithium ion batteries typically experience a similar effect of accelerated degradation from extended periods at low SOC as well. The resiliency of a given battery to these different aspects varies based on cell design details and materials used for the cell and thus it is crucial to have a good understanding of a given battery's sensitivities when selecting for an application.

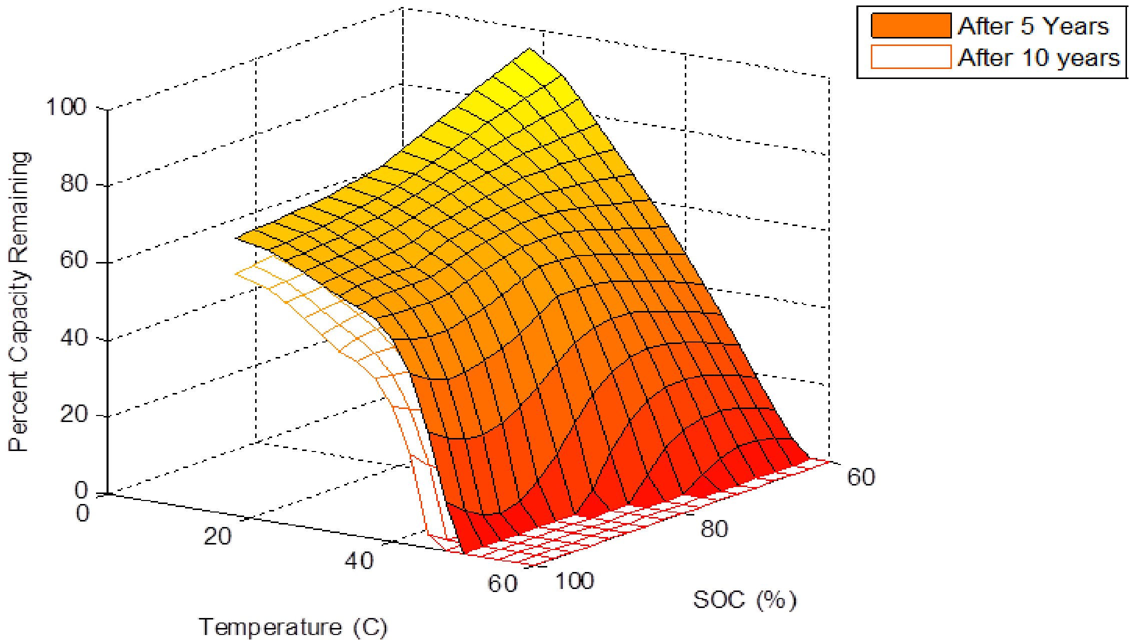

Figure 3.5. Evaluation of expected capacity shows the detrimental effect of high temperature and high SOC on calendar (standby) loss

Beyond calendar effects, battery degradation and capacity loss is also highly influenced by the manner in which it is cycled. Temperature is paramount, as it is with calendar effects; but in addition many aspects of the cycles themselves affect degradation rates. Higher levels of current (or power) as well as larger changes in SOC (sometimes referred to Depth of Discharge, DOD or Delta SOC, DSOC) will result in more rapid degradation. Continual charging and discharging of the batteries from completely empty to completely full will in general degrade a battery faster than smaller partial cycles. For maritime applications requiring ten year life time, systems are typically dimensioned such that the cells are neither charged to their full capacity nor are they fully discharged – typically only some reduced amount of energy is actually used, referred to as the 'available energy,' relative to the full, electrochemical energy of the system. The charge and discharge

SOC limits will depend on the application (duty cycle), cell design and desired lifetime. The voltage or SOC range may also change with the age or state of degradation (State of Health, SOH) of the battery system. Using a more limited SOC range increases the lifetime of the battery but therefore requires a larger battery to perform the same operation, thereby increasing cost. This balance of cost and lifetime is a critical question for battery system design, requiring in depth evaluation of the duty cycle and battery technology in order to ensure optimal cost and performance. Accurate knowledge and analysis of the duty cycle incorporates aspects such as determining duration and necessary power or c-rate values. This analysis is key for evaluating system sizing and potential benefits, as well as determining the best-fit battery technology or chemistry. These aspects are discussed in additional detail in Appendix D.

3.3 Typical maritime battery system configurations

The generic battery system applied as basis for the recommendations in this Handbook is outlined in the block diagram in Figure 3.6. As shown, the main components of the generic battery system are the cells, the hardware needed for making battery modules and strings, the required components for thermal management, safety features as contactors and fuses, bus-bars and high voltage cabling, electronics, voltage and temperature sensors and low voltage cabling and connectors. A brief explanation of some of the most important terms applied is given under the figure. Further details on battery systems and components, operational modes and important parameters are provided in Appendix A.

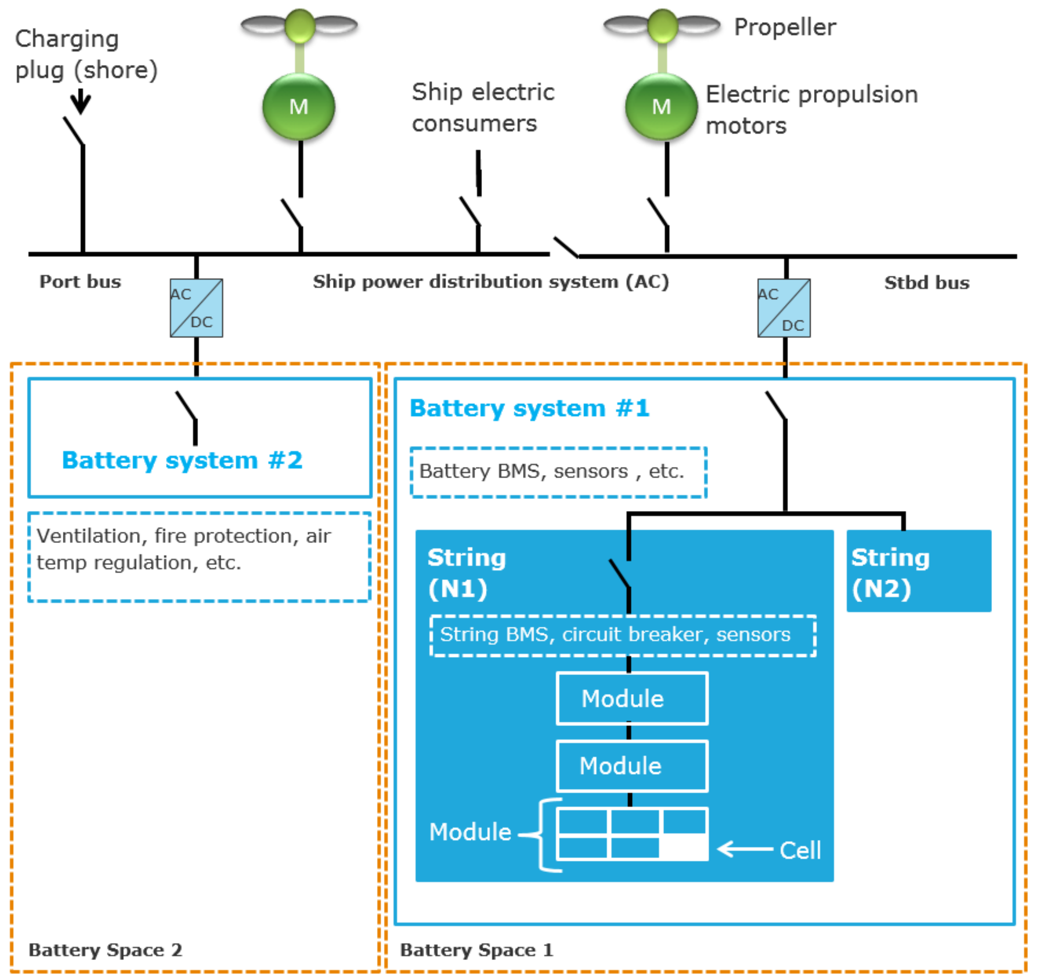

Figure 3.6 Generic maritime battery system

- **Cell –** The cell is the smallest electrochemical unit.
- **Module –** Assembly of cells including some level of electronic control and/or monitoring. The smallest unit that can be electrically isolated in an assembled battery system. For some systems, the modules may consist of blocks of cells with some electronic monitoring included.
- **String –** Smallest unit with same voltage as the system level (e.g. serial connected cells or modules). This can also work for the intended purpose as a standalone unit.
- **Battery system –** One or more battery strings including all required systems for the intended purpose
- **Battery space –** Physical installation space including walls, floor, ceiling and all functions and components which contribute to keep the battery system in the defined space at a specified set of environmental conditions (e.g. temperature or humidity level)
- **Battery Management System (BMS)** – A collective terminology comprising control, monitoring and protective functions of the battery system. The main battery control software and protection is as important to ensuring battery safety and performance as the energy storage technology itself. The BMS must monitor system voltage, State of Charge (SOC), State of Health (SOH) and temperature. In addition the BMS is responsible for ensuring adequate voltage balance between cells in the system. This primarily requires compensating for individual self-discharge rates between the cells by draining the cells with the lowest self-discharge rate through a resistor. The BMS is responsible for ensuring these systems operate within design spec and that the battery accurately responds to the operational commands it receives from the ship power system. More information about the BMS is provided in section 5.4.
- **Ventilation** – In the case of abuse or failure, lithium-ion batteries will typically generate gases preceding, and in addition to, combustion events. The composition of these off-gases depends mostly on the electrolyte composition, state of charge, temperature, internal cell pressure and cell age, but has been found to be corrosive, toxic and flammable, as well as potentially explosive. These characteristics need to be considered in design of the battery space and it's ventilation system, and the design should prevent build-up of flammable gases and dispersion of toxic gases to other ship compartments. Utilization of sensors for offgas detection is a vital aspect of safe system design. The total amount of gas generated in a thermal event depends mostly on cell size, cell design, electrolyte composition, cell temperature, cell internal pressure, state of charge, cell age and whether a thermal event spreads from cell to cell. The consequences can therefor range in severity from less than that of a thermal event in a mobile phone to very severe.
- **Fire protection** – Battery systems pose a fire risk and the design therefore need to include an appropriately designed containment and/or fire extinguishing system. One challenge related to a battery fire is the range of different substances that might burn. This includes solid combustibles (often categorized as class A fires), flammable combustible liquids (class B) and electrical fires (class C) and metal (class D). Battery system fires can include all these categories of substances at different stages making efficient fire protection (and cooling) quite challenging. Due to the importance of heat dissipation, water is often being selected as the preferred cooling medium.
- **Thermal Management System** – Depending on operational conditions, battery systems may produce significant quantities of heat. At the same time, they are sensitive to operation at high temperature, which can pose both a safety risk and a performance risk leading to accelerated degradation. Therefore, many battery systems require cooling systems, which are typically by air circulation or liquid cooling. Each approach has its pros and cons, and the cooling system design should be appropriate to the application, battery type, design and location.

- **Power system integration** – The battery installation must be properly integrated into the power system as well as the power management system. The power system may consist of shore connection, generators, distribution and consumers.
- **Inverter** – A battery system operates electrochemically using DC power, and will require an inverter or power converter in order to interface with an AC ship distribution system. However, these inverters provide the additional capability to produce reactive power, voltage and frequency support as well as increase power factor throughout the ship. Depending on interface voltage and desired function, the battery can be installed on any bus or switchboard on the ship, allowing a great deal of flexibility with regard to placement.

3.3.1 Battery space and location

The battery space is the physical enclosure in which the batteries are located and it includes all functions and components which contribute to keep the battery system in the defined space at a specified set of environmental conditions. Depending on the application of the battery system, there are certain important elements to consider. DNV GL Class rules require that the battery space has to meet a general fire integrity level of A-0 and A-60 towards any muster stations or evacuation routes. If the battery power shall be used for propulsion under normal operation, dynamic positioning or other relevant operations, it shall also meet a fire integrity level of A-60 towards any machinery space of category A as defined in SOLAS Reg. II-2/3. The battery space can also not be located in the forward collision bulkhead.

For High Speed and Light Crafts according to the HSC-code, the battery space can be defined as "Areas of major fire hazard" according to HSC Code Chapter 7.

It is recommended to initiate the safety assessment in the design phase once the battery provider has been established. Reference is made to further details relating to these studies as given in Appendix A. The safety assessment required by the DNV-GL class rules shall verify or override the requirements stated in the DNV-GL class rules with respect to arrangement, environmental control and fire safety of the battery space.

3.4 System topologies with maritime batteries

Chapter 3.1 outlined benefits of utilizing large batteries in the maritime industry. In order to achieve these benefits, the maritime battery system has to be integrated into the electric power system. Traditionally, on board a ship there is an electrical power system for the "hotel load" and the auxiliary systems. The propulsion power is taken care of by a combustion engine, called main engine. The power for the electrical load is produced by generator sets consisting of an electrical generator driven by a combustion engine. These engines are called auxiliary engines.

Ships that also use the electrical power for propulsion are now becoming more common. In typical ships the operation requires variable power demand (e.g. offshore supply vessels) or flexible spaces (e.g. cruise vessels). There are several different ways of integrating a battery system into an electric power system. To illustrate some of these possibilities, the symbols shown in Figure 3.7 are used to build different topologies where maritime batteries are integrated.

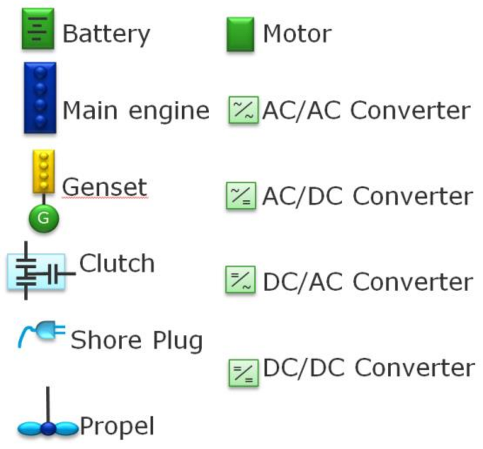

Figure 3.7 Symbols for electric components. In this report, "Genset" means the engine and generator set. For the converters, a transformer may be added to minimize noise that can influence the BMS or battery system.

3.4.1 Traditional Mechanical Propulsion

Figure 3.8 shows a battery integrated in the electrical system for a vessel with traditional mechanical propulsion.

In this case the battery will be effective for smoothing the connected hotel electrical loads and contribute to handle large load steps or peaks. When the large load steps are reduced, the number of auxiliary engines may also be reduced. Such system topology will require the class notation Battery (Safety) if the battery system is larger than 50kWh.

In cases where the load can regenerate power, e.g. cranes, the battery can be used to capture this energy. For such applications it is important to keep in mind that the charge discharge round trip efficiency is given by the battery and the converter efficiency. This type of configuration also enables usage of the batteries for standby, providing power without the need for gensets to be running.

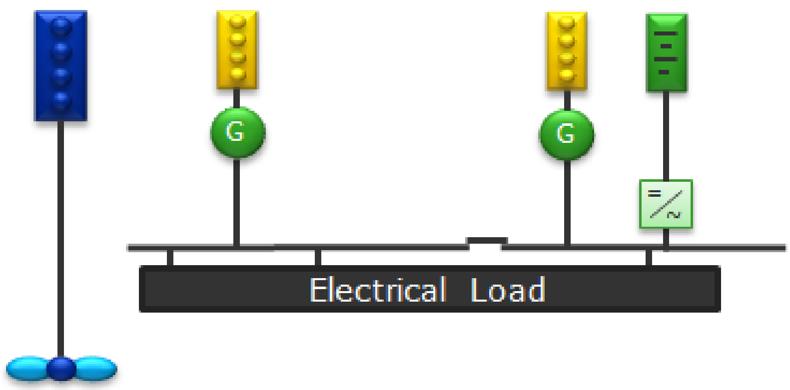

Figure 3.8 Mechanical propulsion with battery hybrid electric power plant

3.4.2 Diesel Electric Propulsion

The batteries can be integrated in a power system for propulsion as shown in Figure 3.9. In this case the battery will provide power to the large propulsion motors. The vessel may run purely on batteries, purely on the generator sets or in parallel operation using both batteries and generators. This topology requires the class notation Battery (Power).

In addition, the batteries can be an energy source for the propulsion, smooth the load variations on the generator sets. By introducing such a hybrid battery system the noise and vibration level on the ship can be reduced. This topology can also facilitate the use of zero emission operation when entering harbor, provided the battery system has the required energy and power.

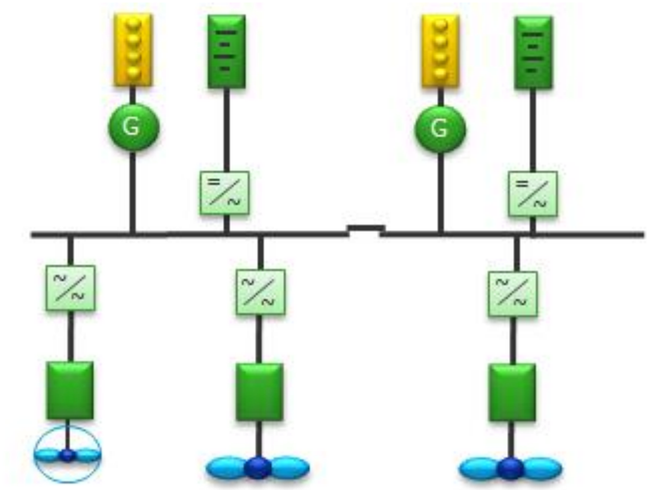

Figure 3.9 Battery hybrid propulsion

3.4.3 Distributed Storage

A challenge with electrical propulsion is the efficiency since the electric converters needed in order to control the speed, torque and power of the propulsion motor typically represents approximately 2% losses. If the batteries are distributed into the propulsion converters, as indicated in Figure 3.10, the losses can be reduced.

Another benefit with a distributed battery concept is that each propulsion unit is independent of a common source of energy. For vessels with high requirement for reliability of the propulsion thrust e.g. redundant dynamic positioning vessels (DP2 and DP3) this might be a smart solution. The requirements for battery capacity and power for dynamic positioning is given in the DNV-GL class rules for dynamic positioning. The battery (power) notation applies to this configuration.

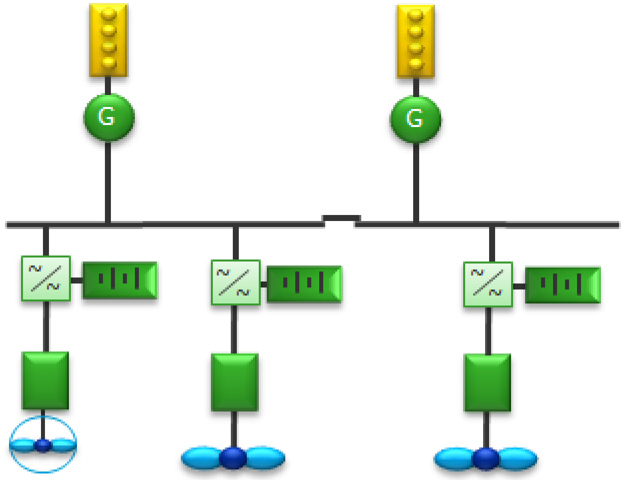

Figure 3.10 Hybrid battery propulsion with distributed batteries

3.4.4 Hybrid with DC Power Distribution

Figure 3.11 shows a power system with electrical/mechanical hybrid solution, a battery hybrid with plug in possibilities and in addition a DC distribution. With a DC distributed system, the speed of the prime movers for the generators can be adjusted to the load dependent fuel optimum level. Hence the fuel consumption is reduced and the environmental footprint is minimized. The electrical/mechanical hybrid solution gives the possibility to produce electricity from the main engine or produce propulsion power by generator sets and batteries. A boost mode is possible (additional thrust power) when the main engine and batteries are running in parallel. The battery (power) notation applies to this configuration.

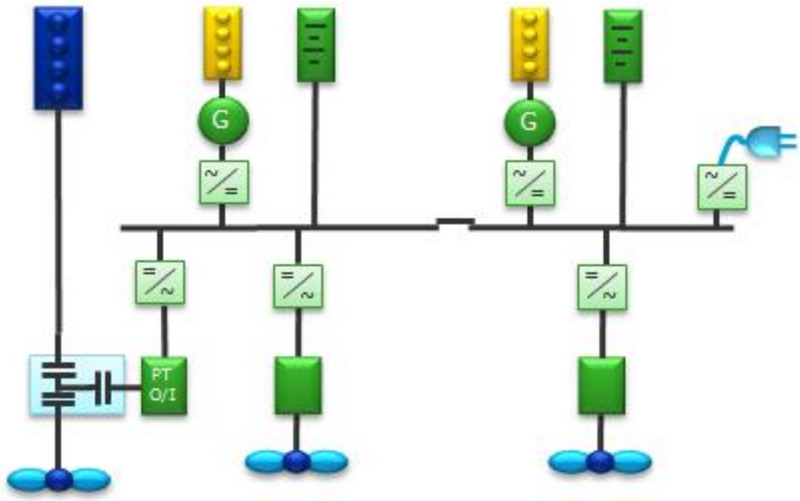

Figure 3.11 Power system with electrical/mechanical hybrid solution, battery hybrid with plug in possibilities and a DC distribution

3.4.5 Full Electric Propulsion

Figure 3.12 shows a power supply system for a purely battery-driven vessel. For this option the batteries will be charged through an AC/DC converter which can be located either on the vessel or on shore. On demand charging from an external electric power supply source is then required. Ferry operations where the voyage is of limited and repeated nature, such as fjord crossings, may utilize pure battery powered propulsion provided that the infrastructure on land allows for proper charging between crossings. Class rules require that two independent battery systems are installed to provide propulsion power in case one system fails. . The battery (power) notation applies to this configuration.

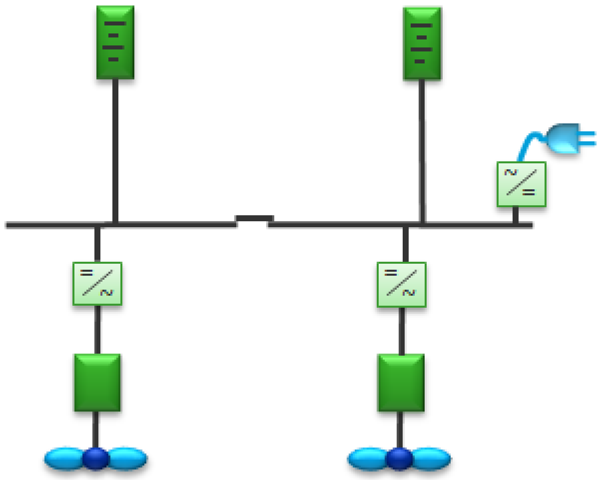

Figure 3.12 Battery propulsion for an all electric ship

3.5 Battery Safety Considerations

Batteries present many opportunities for benefits and increased system performance. However, the risks posed by battery systems with regard to safety are different than those of traditional power system components, and thus require particular attention. These risks are manageable and it is feasible to ensure a safe battery system, but the risks and challenges need to be identified and appropriately taken into account with respect to battery system selection and integration. It is a main goal that the safety and reliability of a vessel with a large lithium battery installation shall be at least at the same level as a conventional vessel.

It is strongly recommended to evaluate critical failure modes and related safety and economic aspects from the beginning of the concept development. The failure modes will nominally be identified in the safety description and safety assessment (discussed in detail in Section 5.1.1 and Appendix A), as formally required by class rules. Appendix B provides a more detailed account of battery safety events. These documents identify key aspects of the design that will affect safety and describe the philosophy of design, operation and approach. The Safety Description relates to the battery system itself (including propagation, monitoring and BMS, and thermal management) while the Safety Assessment pertains to how the battery system integrates into surrounding ship systems with regard to requirements for safe operation.

This section provides an overview of safety aspects of lithium ion battery systems for general information as well as consideration in the assessment phase. In most cases, a lithium ion battery failure will result in temporary inoperability (requiring service) or potentially some reduced level of capacity or power. However, it is possible for a lithium ion battery failure to result in a safety event. These scenarios include the release of off gas, which can result in explosive and/or toxic environments, and thermal events (fire or thermal runaway). The probability and possible consequences of such events depends on design and manufacturing of system and components, as well as what specific protections that are put in place. At the most fundamental level, the battery cell technology utilized plays a large role in determining the risks and requirements relating to safety. This includes:

- Cell chemistry: some cell chemistries may go into thermal runaway at lower temperatures (more easily) than others. Additionally, during thermal runaway some chemistries will inherently produce less heat. See Section 3.2.1.
- Cell size (capacity): larger individual cells will produce more heat under a thermal event or more gas under an off gas event, and thus present an increased risk and the need for more protection.
- Cell form factor: different cell types (cylindrical, pouch, etc) will have differing levels of resiliency or tendency towards different types of failure modes. See Table 3-1.
- SOC: higher levels of SOC within a given cell, or battery as a whole, will produce greater amounts of energy in the case of a thermal event. This will thusly result in higher temperatures as well as greater amounts of material combusted or released as gas.

These items address the probability of a single cell failure and its consequences. All of these issues must also be considered within the context of cell environment – particularly temperature; but also humidity, corrosivity, pressure, and the level of isolation from these potential abuse mechanisms. The most significant risks with respect to battery system failure are in the case that a single cell failure propagates or cascades to other cells, with the then elevated risk that it will propagate to an even greater number of cells in additional modules. As shown in Figure 3.6, multiple battery cells are arranged into larger modular packages which are then interconnected – each of these packages is typically referred to as a module. Thus, the design of the module and its protections are vital with regard to preventing the propagation and cascading scenarios that can result in large scale, high risk events, potentially compromising overall vessel safety. This means protecting against cell failure from propagation to other cells as well preventing failures from cascading to neighboring modules. Modules must be designed under consideration of the size and chemistry of battery cells used, because larger cells of a more potent chemistry may have significantly higher requirements for isolation to prevent propagation. Moreover, it must be considered that at this point of technology development, absolute elimination of propagating failures consuming more than one module is a challenging undertaking. Thus, systems should in many cases be designed to handle worst case scenarios, including large volumes of flammable or explosive gas in the battery room as well as substantial heat loads.

Beyond considerations of the physical design and arrangement of the battery system, safety considerations are highly interrelated with other key battery design factors regarding performance and quality. Key aspects with possible implications for safety, reliability, life, cost and overall operability of the vessel are:

- Relevant experience of the battery system manufacturer, supplier and yard.
- Quality of the design and manufacturing of the battery cells.
- Operational limits of the battery and control system quality.
- Thermal management of the battery system.
- Sizing of the battery system taking into account the relevant load cycles, charge and discharge patterns.
- Battery space design and operation of safety systems.

4 MARITIME BATTERY IMPLEMENTATION PHASES

The process of installing battery system onboard marine and offshore units will generally follow normal practice for marine applications. Figure 4.1 illustrates the ship building process and the responsible party for the different project phases.

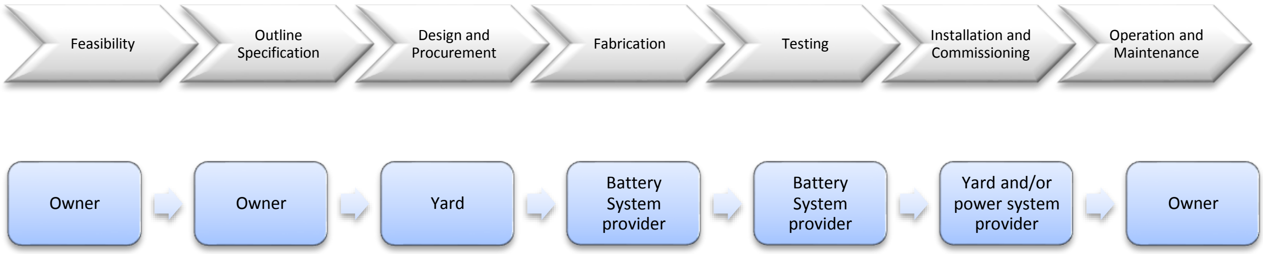

Figure 4.1. The battery system in the shipbuilding process and the responsible party

4.1 Feasibility

It is recommended to undertake a feasibility study before deciding to use a maritime or offshore battery system.

The purpose of the feasibility study is to evaluate alternative solutions as appropriate for the case considered. Whether it is a pure battery or a hybrid solution, a clear objective of the case needs to be established. The motive for the study, if it is for economic, environmental or other reasons or a combination of these should also be established in order to obtain the objective of what one wants to achieve.

Expected operational modes and operational profiles, relevant load cycles, targeted life of the system etc. need to be considered in the feasibility studies. Evaluation of strengths and weaknesses (e.g. SWOT analyses) of alternative solutions with respect to technical issues, environmental aspects and economy are relevant in this phase. The results of the feasibility study, which should include a rough sizing of the whole power system with related engines, batteries and/or charging facilities, will be used to determine whether the project should go ahead to the next phase.

The costs for a battery system depend on the energy storage quantity and the power capabilities of the system. Therefore, getting the dimensioning correct is a key design issue. This dimensioning will be mainly determined by the power and energy requirements of the charge and discharge cycles the battery is expected to provide. It is therefore important to establish sufficient information about the operational profile of the system/vessel. Historic information about traffic patterns (e.g. from AIS) and operational experiences from similar systems/vessels can be important input. Battery degradation (ageing or calendar effect, quantity and magnitude of charge/discharge cycles, how fast charging/discharging occurs, the range of SOC used in operation, and the temperature of the batteries) has to be taken into account very early in the process as this will be an important parameter in sizing the battery, and its ability to perform intended functions throughout the battery system’s service life. Possible locations for the battery system should also be considered at this stage and especially for smaller vessels where weight distribution will have an effect on overall performance of the vessel. In addition the battery location is important in order to ensure a suitable environment for the batteries.

Appendix E gives an example of technical feasibility services as well as analytical results of the life cycle environmental impact of a battery system. Appendix D provides an explanation of the DNV GL software tool Battery XT and how it can be used to analyze a given duty cycle to provide battery sizing evaluations (such as power and duration) and help determine the ideal technology or chemistry for a given application.

4.2 Outline Specification

In the case of a successful outcome of the feasibility study, an outline specification should be written in order to scope the intended system for purchase and further engineering. The outline specification is used by the ship-owner when the yards are invited into the process, even before the bid process is started, and will be part of the basis for this process and price and contract negotiations.

The outline specification includes the main criteria for the system as given by the ship-owner. These will be project dependent, but typically include regulatory requirements, relevant standards, life time requirements, overall functionality, ship load profiles and power input/output requirements. Good and realistic functional requirements for the system will enable a designer/yard to design, price a system and pick the right battery type and vendor for the vessel. In cases of retrofitting battery systems to existing systems some emphasis should be put on the integration between existing and new power management systems.

The following topics should be addressed in the outline specification (based on class rules and ref./2/):

Redundancy

- For pure battery powered vessels, at least two completely independent battery systems need to be installed.
- For hybrid battery powered vessels (battery and internal combustion engine), at least two completely independent power systems are needed. The battery system may be part of one of these.

Safety - The vessel shall be as safe as conventional powered vessels

- The reliability of the complete system must be at least as good as a conventional vessel.
- For non-propulsion cases, loss of battery power shall not affect critical vessel functions.
- Single failure of critical modules, shall not compromise the integrity of the vessel.
- For battery powered vessels, the battery system shall have sufficient useable energy for safe return to port also if one battery system fails.

Battery space redundancy and segregation

- Battery space shall be accessible for replacement of parts of the system.
- Battery spaces shall provide protection against external hazards (e.g. fire, mechanical impact).
- Walls and structures surrounding the battery shall be built to protect the vessel against fire and explosion risks

Battery system

- Shall demonstrate robustness for long term exposure in a marine environment (temperature, moisture, list, trim, roll, etc.).
- Shall be maintainable such that defect parts can be substituted safely and effectively. Competence, technical and process requirements shall be identified.
- Battery lifetime should be such that the business case is economically reasonable.
- The BMS shall communicate critical battery parameters.
- The BMS shall ensure that the battery operates in the safe operating window of the cells.
- SOC and SOH shall be monitored.
- There shall be alarms and shutdown functions on several levels.
- Important battery parameters shall be logged and stored in a non-volatile memory.
- Earthing of batteries: isolated system is recommended (isolated positive and negative terminals).
- If the battery system is equipped with a remote logging/diagnostic system, it should be protected sufficiently against intrusion.
- A maintenance and operational plan including emergency operation shall be established.

For pure battery powered vessels

- Enough charging shall be possible during port stay to keep an acceptable state of charge.
- Remaining range or time shall be displayed on the bridge as well as engine control room.

4.3 Standards, Rules and Regulations

Table 4-1 and Table 4-2 list relevant standards, rules and regulations at the time of publication of the Battery Handbook. This listing will need to be examined for updates due to new standard, rules and regulations that might become available at a later time. Alternatives to the requirements stated in the mandatory rules and regulations listed in Table 4-1 may be applicable provided that the overall safety and reliability level is found to be equivalent or better than that stated.

DNV GL class rules will be mandatory for vessels built to DNV GL class. It also has to be noted that the authorities of the applicable flag state may have additional or supplementary requirements. Of particular note at the time of publication are the requirements of the Norwegian Maritime Authority (NMA). Specifically referenced is the Circular listed in Table 4-1: 'Guidelines for chemical energy storage - maritime battery systems' released by NMA 18 July 2016. This document outlines specific tests which are required to demonstrate a sufficient level of propagation protection and offgas risk assessment for any ship under the Norwegian Flag. Given the rapid development of the technology and the need for rules and regulations to also evolve it is recommended to verify the most current requirements when designing a vessel which shall use battery power.

Additionally, the UK Maritime and Coastguard Agency has issued a Marine Guidance Note pertaining to lithium-ion battery installations – MGN 550 (M+F)[4]. This document provides guidance as far as best practice with regard to battery system design, storage & transportation, installation, operations & procedures, maintenance and disassembly/recycling.

For additional reference, DNV GL has also compiled its experience with grid-connected battery systems in the comprehensive Recommended Practice GRIDSTOR, available for free download online[5].

Rules and standards
DNV GL Rules for classification of ships Oct-2015, Battery Power
DNV GL Rules for classification of ships Oct-2015, Dynamic positioning
DNV GL Rules for classification of ships Oct-2015, Electrical installations
DNV GL Rules for classification of ships Oct-2015, control and monitoring systems
DNV GL CP-0418, Type Approval of lithium batteries
Norwegian Maritime Authority, Circular Series V, Guidelines for chemical energy storage - maritime battery systems
IEC 62619 Secondary cells and batteries containing alkaline or other non-acid electrolytes (will be published in 2017)
IEC 62620 Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for use in industrial applications Edition: 1.0 (2014-12-01)
UN Manual of Tests and Criteria, UN38.3[6]
IEC 62281 Safety of primary and secondary lithium cells and batteries during transport Edition: 2.0 (2014-02-01)
UL1642 Standard for Lithium Batteries, edition 5 (2012-03-13)
UL1973 Standard for Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications
International Convention for the Safety of Life at Sea (SOLAS),1974
IEC 60529 Degrees of protection provided by enclosures (IP Code) Edition: 2.2 (2013-10-01)

Table 4-1 Relevant battery rules and regulations (based on input and experience from DNV GL Class rules)

[4] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/519596/MGN_550_Electrical_Installations_-_Guidance_for_Safe_Design__Installatio....pdf

[5] https://www.dnvgl.com/energy/brochures/download/gridstor.html

[6] UN 38.3 approval is necessary for all lithium-ion batteries, as it is required for systems to be lawfully transported.

Rules and standards	Section	Comments
IEC 61508 Functional safety of electrical/electronic/ programmable electronic safety-related systems - Part 0: Functional safety and IEC 61508 Edition: 1.0 (2010)	-	Relevant for the BMS
IEC 60092-504 Electrical installations in ships - Part 504: Special features - Control and instrumentation Edition: 3.0 (2001-03-22)	-	Relevant for the BMS
DNV Recommended Practice DNV-RP-A203, Technology Qualification, July 2013	-	Technology qualification
EN 50110 Operation of electrical installations -- Part 1: General requirements Edition: 2.N (2013-06-01)	-	Supporting standard
IEC 61508 Functional safety of electrical/electronic/programmable electronic safety-related systems Edition: 1.0 (2005-01-20)	-	Supporting standard
IEC 61511 Functional safety - Safety instrumented systems for the process industry sector Edition: 1.0 (2003-12-19)	-	Supporting standard
IEC 62061 Guidance on the application of ISO 13849-1 and IEC 62061 in the design of safety-related control systems for machinery Edition: 1.0 (2010-08-01)	-	Relevant for the BMS
ISO 26262 Road vehicles -- Functional safety Edition: 1 (2011-11-14)	-	Supporting standard
IEC 62133 Safety Test Standard of Li-Ion Cell and Battery	-	Relevant for battery

Table 4-2 Supporting rules and regulations for electrical testing

5 BATTERY SYSTEM DESIGN AND PROCUREMENT

When the ship building contract is signed, the responsibility and further design work is normally transferred to the yard. The yard prepares procurement packs for the various system components. It is recommended that potential battery providers are consulted at this phase.

Main priorities for a battery system for maritime applications are safety, reliability and sufficient life for the system to be economically feasible. All components in the battery systems must be of good quality to secure a safe and reliable system throughout the system’s lifetime. The integration and testing of the complete battery system is of similar importance as the quality of its single components. Once the battery provider has been established, it is strongly recommended that a safety assessment (see Appendix A) of the battery space is initiated at an early stage, since several safety aspects may depend on the battery chemistry and configuration.

For class approval, both a safety description and a safety assessment are required (two separate documents). The safety description describes battery cell chemistry and design and includes identification, assessment and documentation of the safety hazards that are relevant for the specific battery system. This document should describe the primary features of the battery with regard to safety, and a philosophy on how these are all interrelated and the system is able to ensure safe operation. In the class setting, the safety description is the battery manufacturer's responsibility. It is recommended to consider these battery system safety issues as part of the procurement process.

The safety assessment will be required to be submitted for approval for vessels being classed by DNV GL. This assessment shall evaluate the specific battery system hazards and their potential consequences as applicable for the specific installation including the battery space and the integration of the battery system on board the vessel. The responsibilities are summarized in Table 5-1.

Battery manufacturer's responsibility	System integrator's responsibility (typically yard or designer)
Safety description Describing the hazards related to the battery system taking into account all relevant considerations such as sensors, monitoring and propagation protections. More details: chapter **5.1.**	Safety assessment (using the safety description as input) Cover important aspects related to the battery space and system integration. More details: Appendix A.

Table 5-1 Documentation responsibilities according to DNV GL class rules

As the detailed and in-depth understanding of the battery system in question lay with the battery manufacturer, the safety assessment may be prepared by them on behalf of the system integrator. It can be advisable to engage a third party that can offer both battery and safety assessment expertise (i.e. including competence on the risk factors described in chapters 5.1 and Appendix A) to carry out these assessments.

5.1 Safety Description

The safety description as required by the class rules (Table 4-1) shall cover key safety elements and philosophy specific to the battery system. Class rules also require a more detailed Safety Assessment, which then addresses risks and hazards specific to a given installation. Requirements for this analysis are given in Appendix A. The safety aspects and failure modes that should be considered specifically for the battery system and design itself, and addressed in the Safety Description, include:

- Internal cell failure
- Internal or external short circuit
- Overcharge or overdischarge
- Over-temperature
- Excessive external heating or fire

Thereafter, the main focus is to assess the risk for propagation of the initial event/relevant failure modes and the consequences of such propagation with respect to escalation to more cells (or modules). Such assessment will include consequences as:

- Gas development (toxic, flammable, corrosive)
- Thermal runaway (including cascading protections and isolation mechanisms)
- Fire risk, including external heating or external fire
- Explosion risk

It is possible to present a worst case approach in the safety description, but in this case the worst case scenario selection needs to be justified.

Safeguarding measures like ventilation, explosion venting, detection, strengthening of walls, and alarm systems and fire protection and extinguishing should be included. As the safety description is prepared for a battery system without the context of a specific ship application, this will need to be further detailed in the safety assessment (Appendix A).

The evaluation should include relevant consequences for operability, ship crew and ship including e.g. toxicity, corrosion and structure integrity.

Other relevant safety issues that need to be included are:

- External damage (due to grounding, collision etc)
- Submersion risk (due to flooding or fire extinguishing)
- Safe charging and discharging characteristics (deviations from this is a relevant failure mode)

The aspects regarding the battery safety description mentioned in this section can be used as a basis for compiling the document. There could be elements to the battery that are not specifically mentioned and the above paragraphs have to be considered as an aid only and not to be considered as the definite list of items to include.

5.1.1 Failure modes

Several factors can lead to failure and temperature increase in a Li-ion battery cell, as illustrated in Figure 5.1. At a certain level of temperature increase, internal components of battery cells will break down; presenting a high risk of fire, ventilation of gasses, exothermic reaction, or even explosion. Comprehensive data from industry experiences are not readily available, but it has been estimated that the lithium-ion battery failure rate is in the range of one in 1 million to one in 10 million systems. /6/

The most critical failures are those that can lead to an internal short circuit (shown in purple in Figure 5.1). The risk for internal short circuit can be controlled by proper battery design, manufacturing and operation, but it is not possible to completely eliminate the risk for an internal short circuit entirely. All lithium ion batteries use a separator to prevent contact between the positive and negative electrodes under normal operation, and thus the design and composition of this material plays an important role in internal failures. Most importantly, an internal short circuit is not likely to be detected by the BMS. Therefore, proper battery cell and enclosure design is critical to minimize fire and explosion risks posed by internal short circuits. Other sources of failure risk (shown in blue) would nominally be detected by a functioning, capable BMS system – either through electrical sensors (voltage, current), passive electrical protections (fuses, power electronics), or an atypical or excessive temperature increase. Thus, a high degree of monitoring, BMS control and electrical protections are advantageous with respect to safety.

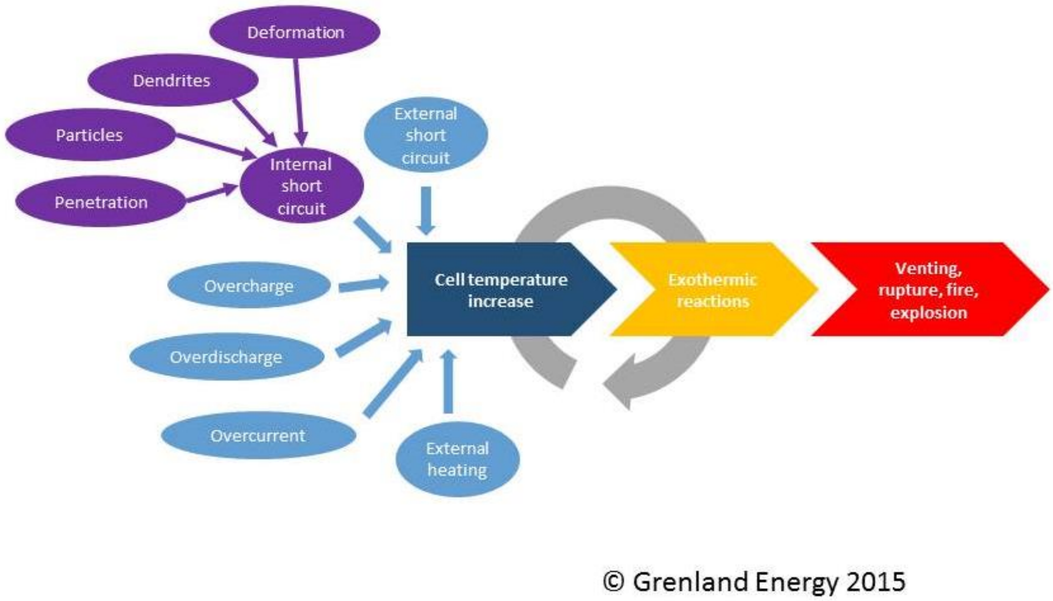

Figure 5.1 Overview of factors that can cause unwanted temperature increase on cell level in a battery system (Grenland Energy)

5.1.1.1 Internal cell failure

Abusive operation, outside of the rated specifications, of a battery cell can cause breakdown of the physical components inside a battery. This can be expected to result in failure of the battery and poses significant safety risks or highly shortened lifetime. Two of these failure mechanisms are explained below.

In case of charging voltage significantly above the allowable upper cell voltage, the electrolyte will start to decompose generating flammable and toxic battery gasses and an increasing proportion of the energy input will be converted to heat due to increased internal cell resistance.

The resulting effects from overheating of Li-ion cells go through several stages: around 60 °C irreversible processes start. If the temperature passes around 80 °C gas generating processes accelerate and pouch cells typically visibly inflate. All Li-ion cells are supposed to handle 130 °C for 10 minutes whereas exposing most Li-ion cells to temperatures above 160 °C usually results in a thermal event. In a thermal runaway situation, the temperature will increase without adding any energy and the cell can catch fire.

Electrical abuse by over discharging, or allowing the cell voltages to drop below the lower voltage limit through storage at low SOC for an extended period of time, can cause progressive breakdown of the electrode materials. The anode current collector can become partly dissolved into the electrolyte. In such a scenario, when the voltage is increased again, the ions which are dispersed throughout the electrolyte are precipitated as metallic particles. This situation represents a possible cause of a short circuit between the electrodes.

The BMS is a vital protection for these failure modes, through its function of voltage monitoring. A high degree of voltage instrumentation is recommended, including the voltage of every cell being monitored. In addition, voltage will vary based on temperature or charge current so the BMS must accurately calculate SOC and voltage by compensating for these factors. This provides the primary preventative measure against over-charging or over discharging of the batteries.

The actions taken in order to avoid thermal and electrical abuse of the battery cells should be covered by the safety description.

5.1.1.2 Internal and external short circuit

An internal short-circuit means that an electrically conductive bridge has been formed between the positive and the negative electrodes inside the battery cell. The majority of such internal-short-circuits do not result in a thermal event. A thermal event can happen if the impedance of the internal short-circuit is high enough to create sufficient heat, but low enough to allow sufficient current to pass and that the conductive bridge is strong enough to not break down when current is flowing. Also, the heating must occur in a location where a high local temperature can induce chain reactions resulting in a cell thermal runaway.

A common root cause which presents the greatest potential consequence is considered to be cell level contamination (internal defect), originating from the manufacturing process, often in combination with cell design flaws or damage during service. Such conditions can produce a short circuit which is one of the greatest risks for undetected, uncontrolled heating (off-gassing) or thermal runaway in a lithium ion battery. To reduce the frequency of thermal events a strong quality focus has to be maintained by the cell manufacturer. It is often this failure mechanism which introduces the design requirement to protect against worst case failure scenarios.

Most internal short circuits are benign and the only noticeable effect is an increase in the self-discharge rate. This increase may be detectable if the increase is large. A small and undetectable increased self-discharge rate is usually not a concern neither for operation nor for safety of the battery system. Spontaneous, severe internal short-circuits are usually impossible to predict or mitigate. Generally, the likelihood of such internal short-circuits is extremely low.

In spite of the low occurrence, for large battery systems it is still necessary to ensure an acceptable outcome from a cell level spontaneous internal short-circuit. If propagation of a thermal event is limited so that it does not spread throughout the entire battery system, this is normally considered adequate. If a thermal event can be limited to cell level, this is from a safety point of view usually the best.

There are means available to protect cells from severe outcomes of an external short circuit. This protection could be internal in the cell (such as CID protections), part of the cell to cell interconnects or part of the module protection system. The possibility to include cell level protection measures depend on the cell type and construction. If special cell design or choice of separator material helps prevent such internal failures it has to be included in the safety description.

5.1.1.3 External heating or fire

Active, and especially liquid-based, cooling systems provide the greatest capability as far as prevention of excessive battery temperatures. However, in many systems which can claim advanced thermal and power management of the battery system, external fires still remain a high potential risk. The effects of an external fire or excessive external heating, and whether the design has taken this into account, shall be covered by the safety description.

5.1.2 Potential gas development

Li-ion battery systems are sealed systems with nominally insignificant external gas generation during normal operation. As described in Section 5.1.1, a range of abusive factors affecting a battery cell can lead the electrolyte to start to decompose and further to formation of gasses inside the cell. The gas quantity and composition will depend on the chemistry of the cell, the voltage, the temperature and also the failure mode. Tests have shown that gases produced are likely to be both toxic and flammable, and potentially explosive. Thus, it can be challenging to determine both representative and worst case scenarios. Therefore, identification, assessment and documentation of the amount of gas and which gases that can be emitted is necessary. Capabilities for detection and ventilation are key in protecting against these risks.

The gasses produced during a lithium-ion cell failure will typically consist of many individual components – including, but not limited to: hydrogen, CO, CO_2, DEC, MEC, C_2H_4, CH_4, HF, HCl, HCN. Gases that are produced, and whether they are self consumed by the fire, will also depend on the temperature of the fire. Mixing of different gases might pose a combined risk effect that would not be identified by analyzing the individual gases separately. Lower and Upper Explosive Limits (LEL/UEL), self-ignition levels and toxicity are parameters that can be found by analyzing the combined composition of the emitted gases. These factors are key for determining ventilation requirements. Programs and procedures that can be used are DNV GL Phast, and commercial thermodynamic and CFD programs such as HYSYS, Chemcad, KFX and FLACS.

The gases should be classified according to the potential risk. Possible risk factors include flammability, formation of an explosive atmosphere, corrosivity or toxicity etc.

Calculations giving an estimate of the expected volume of flammable gases that might be generated is needed to understand the possible safety implications of gassing from a battery. This is required along with test results indicating expected quantities and composition of gasses, as well as tests to indicate the how many battery cells (or modules) that may be involved in an event. If the electrolyte composition is known, the worst case gas volume and flammability can be calculated by determining the maximum generation of flammable gases from the electrolyte constituents.

Quantities of gas produced will depend on factors like SOC, temperature, and failure mode. When gases are emitted, they will create a gas cloud which will mix with the surrounding air. In order to determine the fire and explosion risk, the size of the flammable gas cloud should be determined. The cloud size depends on the rate at which the gas is emitted and the ventilation conditions in the room. The transient rate of gas emitting from the battery should be included in the safety description expressed as a function of time, or with a constant rate over a given time.

Reference is made to Appendix A for further details on needed assessments to assess the installation of batteries on board a ship.

5.1.3 Thermal runaway and ignition

Thermal runaway is normally defined as a temperature increase exceeding 20˚C/min and refers to rapid self-heating of a cell (or several cells) derived from an exothermic chemical reaction. The internal temperature and pressure increase may lead to melting of the separator (causing an internal short). The consequence is evaporation and decomposition of the electrolyte and subsequent venting of the cell as the pressure increases above the mechanical strength of the housing. The cell temperature will typically exceed 200˚C, potentially reaching 680˚C (the melting point of aluminum) or peaks of 800˚C during a thermal runaway event. Ventilation requirements Different types of cells will have different types of housing and key safety features, including CID (Current Interrupt Device). Oxygen is available when gas vents out from the cell and mix with the surrounding air. Limited amounts of oxygen can also be available from oxide-based cathode materials. Ignition can be caused by sparks from the battery, electronic equipment or by the high temperature. The auto-ignition temperature of the most common electrolyte solvents is in the range of 440˚C - 465˚C. The further consequences can be a gas fire if it is ignited immediately or an explosion followed by a fire if it is ignited at a later stage. The risk for a thermal runway situation to propagate to adjacent cells, or modules and quickly spread out through the whole battery installation depends on the battery configuration and safety system. It is therefore important that this risk is properly addressed and managed.

5.1.4 Explosion risk

The risk of an explosion is closely related to the gas development and has to be analyzed based on the gases that can be emitted from a battery system in a failure situation. An assessment of the risk of an explosion within the battery module(s) is a part of the safety description. The corresponding risk for the installation in the battery room is part of the safety assessment (Appendix A). The measures taken in order to avoid explosions and planned measures to prevent explosions or limit the consequences can be included. If there are special precautions to be taken during a thermal event it must be covered.

The first step is to obtain an accurate account of the amount of gas that can be expected to be released, and calculate the possible gas cloud volume assuming the gas emitted will form an ideal mix of stoichiometric gas. Data regarding expected gas release should be collected from testing on the specific cell in use, based on clearly stated conditions, because significant variation exists between manufacturers, chemistries, etc.

Reference is made to Appendix A for recommendations on how to undertake an assessment of explosion risk for a battery system installation. Following this procedure, it will be possible to design the room to a lower explosion pressure by e.g. installing pressure relief panels/weak walls or increasing the size of the room. Ventilation is also vital to reduce the probability of explosions from smaller gas releases, hence a reliable continuous ventilation system assumed. It is recommended to validate calculation results against the most recent developments in the areas.

5.1.5 Fire risk

A thermal runaway event is likely to produce a fire that will combust materials and systems nearby. The heat load from such an event should be taken into account. Reference is made to Appendix A for recommendations on how to undertake an assessment of fire risk for a battery system installation. Considerations should include protection of the battery system from an external fire.

5.1.6 Submersion risk

Risks associated with submersion of the battery in fresh water and in salt water have to be covered in the safety description in case effects such as short circuiting, hydrogen gas development or other unfortunate effects could occur.

5.1.7 Detection and alarms

Sensor placement and alarm levels based on the gas composition elements found in the gas analysis covered in 5.1.2 have to be considered along with the means of communicating these alarms to external systems. This will have to be implemented an integrated in the BMS.

Reference is made to Appendix B for further input on detection and alarms.

5.1.8 Fire extinguishing medium

If there are specific requirements to the fire extinguishing medium these have to be included in the safety description. Current classification rules (ref chapter 4.3) state that a water-based fixed fire extinguishing system shall be in place. If this is not suitable for the applicable chemistry or battery system design, it has to be covered by the safety description. Battery fires often have the characteristics of both ABC as well as D class fire at different stages, and thus likely require an advanced consideration of fire-fighting capabilities. In many cases water and/or standard engine room inert gas fire extinguishing is preferred for the battery installation. The preferred method for fire extinguishing will vary depending on the specifics of the installation. Many lithium-ion battery fires are self oxygenating and thus very challenging to extinguish. Cell size, the number of cells on fire and access to the fire are generally very important in terms of how difficult it is to extinguish the fire. Heat removal and extraction is a key requirement of the extinguishing system in order to minimize damage. This is the reason for the class requirements. Battery fires may persist for extended periods so ample quantities of water should be ensured. If the extinguishing system has been identified as a requirement for prevention of thermal runaway propagation, it should be implemented in the same manner as tested.

5.1.9 Safe charging and discharging characteristics

Cell failures resulting in thermal runaway can be caused by operating the system outside of the safe limits of the battery. It is important to keep in mind that the safe limits are not the same as the operating limits. This is valid for the temperature as well as for the voltage and current.

Operating outside the safe limits may cause either temperature rise or other destructive cell effects. Details on these scenarios and effects can be found in Appendix B and Section 5.1.1. Different chemistries will have different requirements and the BMS must be adequately calibrated for each specific battery system. The relevant charging and discharging characteristics and how these are handled by the BMS need to be covered in the safety description. It is recommended to perform a third party review (e.g. by Class) of the BMS operation and ability to respond to unexpected modes of battery system operation. More information about the electronic control system is provided in Section 5.4.

5.2 Lithium-ion battery cells

Ideally in a lithium-ion system, the voltage, current and temperature of each single cell in the system is monitored and protected at all times. However, many simplifications can be made to this arrangement which are reasonable and provide reduced cost and complexity. Still, it is advantageous to have the highest degree of monitoring that is possible. Many systems, for example, monitor voltage of each group of cells at the lowest level. A FMEA analysis, a HAZOP or similar can provide insight as to whether the instrumentation level of the system is appropriate and to a sufficient degree to ensure safe operation.

There are a large number of manufacturers of different variants of lithium-ion cells. Cell chemistries, are reviewed in Section 3.2.1, can be further combined and optimized for different needs or applications. For some applications, the main focus is on high energy density and low cost. For other applications, stable chemistry and long life will be the priority. Other applications can have a focus on power capabilities for charge or discharge or the ability to accommodate high current pulses for charge and discharge. As previously explained, the chemistry alone is not a sufficient measure or characterization of the cell level properties. It is important that the BMS be developed and calibrated for the properties of the specific battery cells that are in use, especially for the purposes of SOC and SOH calculation.

There is disparity in product quality between cell manufacturers. Automated production, proper process control, and robust cell design are crucial elements to ensure good battery cell quality. Premature failure of a cell or group of cells due to manufacturing issues can be an important factor as it can cause a system to be unable to reach its expected service life. More importantly, inadequate cell quality (internal defect) is the primary risk for undetected or protected thermal runaway scenarios.

When the cells are assembled into modules, structural materials must be used around the cells, which are also often designed with the intention of playing a role in thermal management – to conduct heat away from the batteries. Heat is then removed via passive cooling or active cooling with air or liquid.

Modularity in battery system design (typically at the module level) will make it possible to exchange part of the system with minimal downtime or deconstruction in the event of a failure of a cell or sub system. How large, or small, of a portion of the system that can be replaced will depend on the supplier and electrical design to ensure that the replaced portion is able to remain in balance with surrounding modules. It is inadvisable, and uncommon, to combine multiple lithium ion chemistries, or batteries of different ages (SOH) into the same battery pack. Electrical isolation and voltage control (such as through a dedicated DC/DC converter) at each module is recommended for this type of arrangement.

For maritime systems, it is important to choose a cell with properties that can provide an optimum combination of safety, life, performance and cost for the application in question – battery design is a tradeoff of all of these factors. A thorough understanding of all these aspects is required by the team doing the battery system design. To ensure this understanding, independent cell testing or advice from independent third parties who have done neutral testing may be required. See 6.2 for further input on cell testing.

5.3 Electrical system

Battery cells are electrically configured through arrangements of series and parallel connections to form the whole battery pack. Generally there will be some number of cells in parallel that are then connected in series to produce a module of a given voltage, potentially ranging from 12V to more than 100V. Modules are then often connected in series (strings) to produce the systemvoltage level. Strings are then arranged in parallel to produce the required levels of energy for the whole battery system. Electrical protections, such as fuses and contactors, should be present at multiple levels within the battery – such as within each module or at the string level. Other key components electrical system on string level are contactors, fuses, current sensors, pre-charge circuits and service disconnect breakers. It is recommended that each battery string has a separate current sensor in order to detect increased impedance that can lead to overheating. In addition, for systems containing a large number of strings, a group of strings can have a common current sensor.

The electrical connections between the different aggregate levels of the battery system may be connected using cables, bus bars or a combination of these. Low contact impedance for the electrical connections is important to avoid over-heating and control the fire risk, as well as maximum efficiency. Several parallel strings will decrease the risk of overheating from increased contact impedance. It can also ease the detection of elevated levels of contact impedance in the electrical connections resulting in increased safety of the system.

Battery systems generate and store Direct Current (DC) electricity at a voltage level that will change as the battery operates. Power converters are necessary to interface this electricity with the ship power distribution system. In the case of a DC distribution system being used on the ship, a DC-DC converter (or ‘chopper’) will typically be used to control voltage levels. This can also be done at the pack or module level to produce some advantages. In the case of an Alternating Current (AC) ship power distribution system, a bi-directional inverter must be used to convert the DC electricity from the battery. In these AC arrangements it is also advantageous to have a voltage transformer on the battery interconnection. This provides galvanic isolation and a steady voltage to the main switchboard. Power electronics components can be substantial, both in terms of cost and size, relative to the battery. These components will also have losses, or (in)efficiencies, and thus should be taken into account at an early stage of designing the system.

The power converter (whether to DC or AC) is responsible for the majority of battery control with regard to orchestrating charging and discharging operations. The ship Power Management System (PMS or Energy Management System, EMS, depending on the manufacturer) interfaces with the battery through the power converter, typically via droop law, to command charge or discharge functions. Information from the battery, such as status, SOC, and available power level, is calculated and transmitted by the Battery Management System (BMS, described in detail below) to the EMS or PMS. The EMS or PMS then evaluates system load, operational criteria, battery status and input from personnel to make decisions regarding what the power generating equipment should do. The EMS also presents available power and energy levels to crew. It is important that the BMS and PMS or EMS systems are well integrated, both in terms of software and hardware.

5.4 Electronic control system (BMS)

The electronic control system specific to the battery is typically referred to as the Battery Management System (BMS). The BMS is responsible for monitoring voltage, current and temperature limits inside the battery system and evaluating signals to provide indication of when the system operations need to be curtailed. Voltage and current limits are dependent on each other as well as temperature – thus these represent calculations that are both complex and crucial, and are a key responsibility of the BMS. In addition, the BMS is responsible for calculating SOC and SOH. SOC is analogous to the fuel gauge on a car or the percentage remaining on a mobile phone. Users may notice this indication often seems inaccurate, particularly as the battery ages; however, this is vital for a large maritime installation. Accurate SOC is required to give a clear indication of how far a vessel may go on its remaining battery power and also for ensuring that a hybrid system gets its maximum potential fuel consumption benefits. Likewise, SOH is a calculation of how much a battery has degraded over time. This calculation requires a BMS that is highly developed through experience and specifically calibrated to the battery cell being used.

Voltage and temperature sensors are the most vital pieces of equipment for monitoring the battery and ensuring safe and optimal operation. Some systems monitor voltage of every cell (or lowest parallel grouping), which enables the highest level of detection of safety risks or unexpected performance. Temperature sensing requirements depend heavily on module design, but a higher degree of instrumentation can be regarded as advantageous. The key objective is for the system to be able to remove heat from the cells, and in the case that excessive temperature is generated or focused at a location that it can quickly be detected. The need for redundancy for these fundamental measurements depends on design of the safety criticality of the system. A key principle when selecting sensor location is also to ensure that malfunctioning sensors may be detected.

A key feature of the BMS is its ability to monitor cells and ensure balanced operation. If a single cell's voltage differs substantially from those of the rest of the pack it is at a much higher risk of getting overcharged or overdischarged as the system is cycled up and down. In the case that this type of scenario is detected – as is greatly enabled with a high level of voltage instrumentation – it is highly advantageous for the BMS to have some capability to actively correct voltage and rebalance the cell(s). One approach is for some active control of resistive circuits which may interconnect the cells within a module specifically for this task. Typically each assembly of battery modules (eg. pack or rack) will have an additional layer of BMS control. This will likely include control of contactors to isolate the whole battery string in case a fault is detected as well as other electrical controls and monitoring capabilities.

Provision should also be made to monitor and coordinate voltage and power between battery packs. This may be performed by a "Master-BMS" that would then communicate with the PMS/EMS or could be performed by the PMS/EMS. In either case it is crucial to ensure that the communication between the battery and the power management system for the actual application is properly specified for normal operation as well as for situations where a problem has occurred. There are alternative configuration possibilities, one being a dynamic master slave configuration where any of the slave BMS units can have a master role. This increases the availability of the system in case of a master BMS or communication failure.

With respect to all of these responsibilities and features - monitoring limits, balancing cells, calculating SOC and SOH – there can exist a large variation in quality between different BMS systems, and this is a prime indicator of overall battery system quality.

6 BATTERY FABRICATION AND TESTING

Fabrication (manufacturing) requirements will vary substantially depending on the technology used. Some common requirements are described in this chapter.

6.1 Fabrication and Quality Assessment

6.1.1 Product traceability

The safety, performance, life expectancy and reliability of battery systems are potentially very sensitive to a number of factors. Cell level contamination can render a batch of cells vulnerable from a safety point of view. Similarly, other parts or components used in the production or settings used in the production process can give reason for similar concerns. Software controlling safety critical functions and components used for carrying high currents are particularly vulnerable. As are the production settings involving the aforementioned factors. It is therefore very important for the battery systems manufacturer to have a system that can ensure sufficient product traceability to enable preventive actions or recalls in case of systematic faults that can jeopardize adequate safety and performance of the battery system.

6.1.2 Cleanliness requirements

Battery systems are sensitive to contamination with materials that can initiate self-discharge, high impedance, loss of insulation or short-circuits. The cleanliness standards of the manufacturing facilities for each sub-assembly must address the risks associated with the sub-assembly in question. Sufficient internal separation of sub-assembly areas as well as separation of assembly areas, workshop, or packaging areas are usually necessary for both safety and performance reasons.

6.1.3 Sub-assembly and finished product testing

Sufficient testing to ensure that each sub-assembly can be included in the next level of sub-assembly and/or in the finished battery system without posing a safety risk during further testing is necessary. In addition, each sub-assembly should undergo testing, and the testing metrics should correspond to what would be required for the sub-assembly to fulfill its intended function in the system. DNV-GL has prepared type approval test protocols[7] which are recommended for battery systems intended to be deployed in maritime systems.

6.1.4 Operator certification & training requirements

Construction and assembly of battery systems frequently involve operations that potentially introduce risk to operators. National regulations usually specify the required operator training for different voltage levels. In addition, the battery system manufacturer and power system supplier should have operator certification & training requirements and schedules to ensure necessary operator and product safety as well as product consistency and performance.

6.1.5 Health & safety regulations

For the battery system production facilities, company health and safety regulations need to address both regular industrial and electronics manufacturing hazards and particular hazards related to battery manufacturing. Standard industrial operations such as lifting, risk of crushing, crane operations with associated risks are not treated here. The focus is on the particular hazards related to battery manufacturing.

Production of battery systems can pose several hazards. The main hazards are chemical and electrical. Chemical hazards can occur if electrolyte leaks out of the cells, a thermal event or if a short-circuit leads to

[7] CLASS PROGRAMME, Type approval, DNVGL-CP-0418, Lithium batteries, http://rules.dnvgl.com/docs/pdf/DNVGL/CP/2015-12/DNVGL-CP-0418.pdf

overheating internally in the battery or sub-assembly or overheating externally to the battery or sub-assembly. The short-circuit currents can be very substantial even for cells or sub-assemblies containing battery cells and can also lead to serious injuries and loss of life.

A battery manufacturing environment is special in the sense that it will contain sub-assemblies with both high voltage and sensitive electronics. This can pose special challenges for protective gear since conductive materials are preferred to minimize the risk of damage from static electricity, whereas electrically insulating materials are strongly preferred to avoid short circuit risks. To prevent hazards arising from the difference in requirements it is therefore recommended that the manufacturing facilities have different and clearly marked zones for electronics sensitive to static electricity.

6.1.6 Transportation of battery system

In order to ensure safety during transport, nearly all lithium batteries are required to pass section 38.3 of the UN Manual of Tests and Criteria[8] (UN Transportation Testing) which is identical to IEC 62281. Note that this UN regulation is the only mandatory set of regulation for lithium-ion batteries today (12-2013).

Tests 1-8 of this specification are as follows:

T1 – Altitude Simulation (Primary and Secondary Cells and Batteries)
T2 – Thermal Test (Primary and Secondary Cells and Batteries)
T3 – Vibration (Primary and Secondary Cells and Batteries)
T4 – Shock (Primary and Secondary Cells and Batteries)
T5 – External Short Circuit (Primary and Secondary Cells and Batteries)
T6 – Impact (Primary and Secondary Cells)
T7 – Overcharge (Secondary Batteries)
T8 – Forced Discharge (Primary and Secondary Cells)

Further the UN rules defines a large battery to have a gross mass of more than 12 kg and a large cell as a cell with a gross mass of more than 500 g. These definitions are important for the number of samples that are required for the testing.

The UN Transport of Dangerous Goods regulations also defines specific requirements for the packaging used when transporting batteries.

The International Maritime Dangerous Goods Code (IMDG)[9] is relevant in case of transportation on ships, and will also apply for transportation of batteries as goods.

6.1.7 Storage before installation

When storing battery cells a certain degree of self-discharge is inevitable. This could be both reversible and irreversible. The higher the storage temperature and the higher the state of charge of the cells, the higher the losses will be due to increased impedance. As of April 2016, updates to UN 38.3 dictate that cells cannot ship at a state of charge above 30%. It is important that cells and modules are not stored for long periods in a hot environment. If the average storage temperature or temperature during transportation is above 30 - 35 ºC, degradation due to calendar effects will accelerate. Considerations for storage prior to installation shall also include appropriate temperature and SOC safeguards.

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[8] Recommendations on the Transport of Dangerous Goods. Manual of Tests and Criteria. 5th Revised Edition, December 2009. Section 38.3 refers to "Lithium Battery Testing Requirements

[9] http://one.dnv.com/imovega/MemberPages/IMODocument.aspx?resultIndex=0&docId=RES32890ARS&docDate=2016-06-10

6.2 Battery System Testing by Manufacturer

The following tables show examples for the range of test procedures which can be applied to a battery system for maritime applications by the battery system manufacturer. Some of these tests may be defined in the coming standard IEC62619 and will be applicable for testing. The tests are distinguished between TT (Type Test) and RT (Routine Test). The definitions are as follows:

- Type Test (TT): Conformity test made on one or more items representative of the production.
- Routine Test (RT): Conformity test made on each individual item during or after production.

In the case of DNV GL classification, both Routing Tests and Type Tests have to be witnessed by a representative from the classification society. If this is not practicable or for other reasons difficult to arrange, the society may base their approval on test reports if the type tests were conducted at a test institute with accreditation for the tests in question. Generally these tests are done a limited number of times when a new design has been developed and are not required to be repeated unless there is a change of design. Some authorities may require that the tests reports are available for review.

The Routine Tests are less extensive and not destructive as some of the type tests can be since these are to be performed on each individual item. Some authorities may require that for certain applications, the routine tests also have to be witnessed.

Type Tests and Routine Tests will consist of tests at the cell level as well as the system level, also including tests of environmental aspects. Examples of what these tests may consist of is given in Table 6-1 below. Such tests may also reference existing standards, such as IEC 62619 or DNV GL SfC 3.4. A product certificate is based on a case by case evaluation and is mandatory for certain equipment in DNV GL classed vessels. Type approval is general approval for use of the equipment on board DNV GL classed vessels. It has to be noted that product certification may still be applicable even though a type approval certificate has been obtained. Specific requirements of DNV GL can be found at the following locations:

- Class rules for Battery notation can be found in Part 6, Chapter 2, Section 1 of the DNV GL Rules:

  http://rules.dnvgl.com/docs/pdf/DNVGL/RU-SHIP/2016-07/DNVGL-RU-SHIP-Pt6Ch2.pdf
- Type Approval CP 0418 for Lithium Ion Batteries:

  https://rules.dnvgl.com/docs/pdf/DNVGL/CP/2015-12/DNVGL-CP-0418.pdf

Additional requirements of the given flag state or authority should also be taken into account. For instance, the Norwegian Maritime Authority has issued a 'Guidelines for chemical energy storage - maritime battery systems' testing circular as of 18 July 2016; which contains specific tests relating to propagation and offgas analysis.

Examples of Cell Tests	Examples of System Tests
External short circuit	Propagation / internal thermal event
Impact	Overcharge with voltage
Thermal abuse	Overcharge with current
Overcharge	Overheating control
Forced Discharge	Sensor failures
Examples of Environmental Tests	Cell balancing
Vibration	SOC validation
Dry Heat	Capacity validation
Damp Heat	Safety function test
Cold	Dielectric strength (High Voltage test)
Corrosion	Insulation resistance
Flame retardant	Pressure test of cooling pipes
EMC	

Table 6-1 Examples of the kinds of tests included in Type Testing and Routine Testing programs.

7 INSTALLATION AND COMMISSIONING

Experience has shown that failures/unwanted issues often occur in the interface between systems. The interfaces between the battery system and the other ship systems therefore need special focus.

The Battery Management System communicates with the ships Power Management System and key battery information is displayed at the ships bridge. The BMS must have an override function to prevent the Power Management System to perform tasks outside its safe boundaries.

Proper installation documentation must be provided by the battery system supplier.

All interfaces must be tested before the installation can be signed out and a proper test and commissioning plan must be made for the testing to be done at the yard before final sign out. This task should not be underestimated and needs a close cooperation between the battery system supplier, the supplier of the other power plant components and the yard. Functional testing of the safety features of the battery space (ventilation, gas detection, fire detection) must also be performed.

8 OPERATION AND MAINTENANCE

This section summarizes the recommendations identified for the operation and maintenance of maritime and offshore battery systems.

The normal use of the batteries should be fully automatic. There should be no need for manual interaction. Table 8-1 gives recommendations towards a generic operational strategy.

Generic	Only Battery Power	Hybrid Battery/ICE System
• Vessel operation should be as simple and as similar to conventional system as possible, requiring an (automated) energy management system in addition to power management. The BMS keeps battery usage within allowed limits. • Emergency operation procedures necessary (fire, abandonment, etc.)	• Energy management becomes critical • Charging procedure necessary	• Energy management becomes critical if battery used as main source of power • Charging procedure if shore power option

Table 8-1 Recommendations for operational strategy

8.1 Documentation Requirements

The class rules referred to in Chapter 4.3 specify documents that have to be evaluated and approved if the battery is intended to be installed on a DNV GL classed vessel. Table 8-2 lists the documents this process requires submitted. The documentation related to battery system is the battery manufacturer's responsibility. The documentation for battery (safety) and battery (power) is normally either the yard's or designer's responsibility.

Battery system product certification	Battery (Safety)	Additional for Battery (Power)
• Safety description (section 5.1) • Specification or datasheet for the battery system including environmental data • Test procedure at manufacturer • Functional description of the BMS • Block diagram of the BMS • Power supply arrangement of the BMS • List of controlled and monitored points for the BMS • Circuit diagram of the BMS • Calculation report which documents the calculation of SOC and SOH • Operation manual • Maintenance manual • Battery charger documentation if provided by the battery manufacturer (ref. class rules 4.3) • Control and monitoring system documentation for the energy management system[10]	• Internal arrangement plan of the battery space • Vessel arrangement showing the location of the battery space • Safety assessment (ref. Appendix A) • Fire integrity arrangement • Fire integrity penetrations • Fire control plan • Fire extinguishing system documentation • Fire detection arrangement • Fire detection system • Ducting diagram and routing for ventilation of battery space • Test procedure for sea trial and quay • Gas detection system documentation • hazardous area classification drawing with table of ex installations • Electrical schematics of the battery system • System block diagram • Emergency disconnection arrangement • Operation and maintenance manuals	• System philosophy • Electrical load balance

Table 8-2 Document requirements (from battery manufacturer)

The documents referred to in Table 8-2 are mandatory for DNV GL classed vessels. In addition to these, supporting documents for owner and crew should include:

- Hardware manual: Description of the hardware included with the battery delivery.
- Firmware manual: Description of the firmware included with the battery delivery as well as an overview of which units contain upgradeable firmware.
- Installation manual: Description of requirements as to how the system is to be installed.
- Material safety data sheet (MSDS) and/or safety data sheet (SDS) and/or product safety data sheet (PSDS): Documentation intended to provide workers and emergency personnel with procedures for handling or working with that substance in a safe manner, and includes information on how to handle the battery system in an emergency situation as well as information on potentially harmful substances.
- Parts List (high level bill of materials).

[10] Battery charger may be delivered separately, but it is subject to certification.
Energy management system is usually the designer’s, yard’s or system coordinator’s responsibility, but this system is subject to certification

8.2 Operation Manual

It is recommended to establish a plan (Operational Manual) intended for regular use on board, providing information on:

- Load profiles
- Charging procedure
- Normal operation procedures of the battery system included minimum levels of battery capacity
- Emergency operation procedures of the battery system
- Estimated battery deterioration (ageing) rate curves
- Operating instructions for normal and degraded operating modes
- Details of the user interface
- Transfer of control (if more than one control station, or local control are implemented)
- Test facilities
- Failure detection and identification facilities, automatic and manual
- Data security
- Access restrictions
- Special areas requiring user attention
- Procedures for start-up
- Procedures for restoration of functions
- Procedures for data back-up where applicable

The relevant parts of this plan should be implemented in the overall ship operation manual. It should be noted that as a minimum, an emergency operating procedure describing the actions to be taken in case of an external fire or an internal thermal incident, must be kept on board. It is also recommended that the operation manual specifies that any batteries with visible damage should not be used and that such batteries need to be placed in s safe location (away from flammable items).

8.3 Maintenance

Overall recommendations for maintenance are outlined in Table 8-3**.**

Generic	Only Battery Power	Hybrid Battery/ICE System
• Internal diagnostics wherever feasible	• A plan including how and how often the state of charge/health of the batteries is checked/validated shall exist.	• When used as main power: A plan including how and how often the state of charge/health of the batteries is checked/validated shall exist.

Table 8-3 Overall maintenance strategy

A plan for systematic maintenance and function testing shall be kept on-board showing in detail how components and systems shall be tested and what shall be observed during the tests. The plan shall include:

- Verification of the SOH (remaining lifetime of the batteries).

- Test of all instrumentation, automation and control systems affecting the battery system.
- Test intervals to reflect the consequences of failure involving a particular system. Functional testing of critical alarms should not exceed specified intervals (normally 3 months). For non-critical alarms, the longest intervals are normally not to surpass 12 months.
- Acceptance criteria.
- Fault identification and repair.
- List of the supplier's service net.

Different battery systems will have different maintenance needs and maintenance recommendations. This should be included in the maintenance plan. Information about periodically testing should also be included in the vessels unmanned machinery space (E0) manual.

9 REFERENCES

/1/ Qualification of Large Maritime Battery Systems, Project Internal Working Document, rev. AI, 25th Oct 2013.

/2/ DNV GL Guideline for large maritime battery systems, Joint project between ZEM, Grenland Energy and DNV GL, supported by Transnova. Report 2013-1632. Published 2014. https://www.dnvgl.com/maritime/advisory/download-guidelines-large-battery-systems.html

/3/ DNV Recommended Practice DNV-RP-A203, Technology Qualification", revision of July 2013. Source: http://exchange.dnv.com/publishing/Codes/download.asp?url=2013-07/rp-a203.pdf.

/4/ EN 50110 "Operation of electrical installations".

/5/ Battery Fires, a preStudy, Internal project Integrated machinery. DNV GL Report 2014-1666.

/6/ Wang, Q., et al., *Thermal runaway caused fire and explosion of lithium ion battery.* Journal of Power Sources, 2012. **208**: p. 210-224.

/7/ "Blast and Fire Engineering for Topside Structures - Phase 2: Final Summary Report" By Selby and Burgan, Steel Construction Institute, 1998

/8/ CMR Research/Gexcon. *Gas Explosion Handbook*, www.gexcon.com

/9/ DNV GL Rules for Classification of Ships. Part 6, Chapter 2, Section 1 Battery power. http://rules.dnvgl.com/docs/pdf/DNVGL/RU-SHIP/2016-07/DNVGL-RU-SHIP-Pt6Ch2.pdf

APPENDIX A. BATTERY SYSTEM SAFETY ASSESSMENT

DNV GL Class rules (ref section 4.3) require that the arrangement of the battery space is evaluated in a safety assessment. The safety assessment shall cover all potential hazards represented by the specific battery system. Therefore this assessment is expected to be conducted soon after the battery system provider has been established. Based on the battery provider's safety description, a proper assessment of the space in which this system is to be installed can be conducted. The four defined steps of the safety assessment are:

1) Hazard identification

   This means to undertake a structured identification of all relevant accident scenarios and their causes. Most hazards should be available as battery failure modes from the safety description (ref. chapter 5.1.1). The listing of relevant failure modes in Appendix B also provides relevant input. In the safety assessment all possible hazards (failures) need to be assessed in the context of placing the battery system in the actual battery space in the actual vessel including how accidental scenarios might impact the safety of the vessel, its crew and its passengers (as applicable).

2) Assessment of risks, for example:

   a. Gas development risk

   b. Strategy for detection, alarm systems and ventilation

   c. Explosion risk

   d. Fire risk

   e. External risks

   f. Loss of propulsion or auxiliary power for essential or important services

3) Risk control options

   This will typically be to assess possible measures to control and reduce the identified risks

4) Actions to be implemented

Further description of the risk assessments are given in the next sub-sections.

Design scenario definition

The safety description should include information about the toxic, flammable or explosive gases (ref chapter 5.1.2) that might be released due to fault conditions in the battery system. This should provide a basis to establish a design failure case for the battery. It is advisable to include an evaluation of failure probabilities and possible scenario developments in the justification of the design case. The likelihood of different possible developments caused by the different failure modes will be influenced by design and operation parameters for the battery system and battery space, and could also be used in a battery system and battery space design optimization process. Depending on design, a worst case approach might be that one module fails and contribute to generating a thermal/explosion event.

Case by case assessment and documented test results might be required to assess the risk for propagation of an event from an individual cell to multiple cells, or module(s). Such assessments will provide important input to recommendations for appropriate ventilation and possibly other risk controlling measures. In this setting, the main purpose of (additional) ventilation will be to limit the concentration of flammable gasses and thereby reduce the risk for fire.

For instance, it might be cases where gas emissions from a vented small cell in a large room can be acceptable, while this may be different for gas emissions from a bigger cell or a module where the incident propagates between cells. The size and energy content of cells and modules, local ventilation conditions and (free) volume of the battery space will be case dependent and needs to be assessed on a case to case basis.

Gas development risk

The design failure case will define the relevant scenario or scenarios for further assessment, e.g. as the number of cells that can produce gases during a thermal runaway scenario, and the amount and transient behavior of the gas release scenario.

The amount(s) and composition(s) of gases provide the basis for properly addressing important aspects such as emergency ventilation, explosion vent panels or weak walls, emergency operating procedures and physical size and outline of the battery space. Other aspects to be considered include, but are not limited to, placement of ventilation openings due to the gas being lighter/heavier than air, placement of sensors, possible gas pockets in the space where gas accumulates and special considerations such as the need for a breathing apparatus to enter the room.

The gas development resulting from an identified hazard situation depends on the battery chemistry, size and arrangement of the battery system in the battery space. The quantification of gases emitted must be documented, including the duration of the gas leak scenario and the gas components emitted. The gas components have to be classified according to their potential consequence properties (flammable, explosive atmosphere, corrosive or toxic, threat to human safety, or the integrity of the installation). In these calculations and considerations it is of great importance that the real composition of gases are taken into account and analyzed.

If the gas is emitted quickly with a high rate, it will result in a larger ignitable gas cloud than if it is emitted over a longer time. When the gas is emitted quickly over a short period of time (typically less than one minute), the cloud size development is transient with a complex behavior. In order to predict such scenarios, one can be conservative and use that the entire mass of gas will mix to a stoichiometric mixture with air and calculate the cloud size using the density of the mixture. If this is too conservative, it is recommended to run a CFD simulation to decide the flammable cloud size that can occur.

For a scenario with a slow release of gas (lasting several minutes), and a constant release rate, the flammable gas cloud size can be estimated using a CFD model of the battery room with ventilation included. A CFD model also gives the possibility to investigate the effects of different ventilation strategies. Alternatively, a free field, integral plume model like DNV GL Phast can be used to give a rough estimate of the cloud size. The integral models are free field models where no geometry effects are included; hence, if the gas is accumulating in a room with low ventilation, these models will not be able to predict it. The battery room will be an enclosed space, and when gas is spreading within an enclosed area, it behaves different than in the open. The lowest air wind speed possible to use in the integral dispersion models Phast is normally 1 m/s. If the ventilation speed in the battery space is lower than this, a CFD model is therefore recommended to obtain reliable results.

The gas cloud size will develop over time (depending on the scenario) and the maximum size should be used to estimate the potential explosion pressure and the likelihood of ignition.

Strategy for detection, alarms and ventilation

Ventilation should be considered a measure to limit the formation of potentially explosive atmospheres in the battery space in the event of a serious fault condition.

Emergency ventilation can be an effective measure to reduce the risk in case of a failure causing formation of flammable gases from the battery system. Class requirements specify emergency ventilation with a minimum of 6 air changes per hour. The safety description should contain information that demonstrate that the effect of the emergency ventilation including number of changes per hour required will function as intended to maintain gas concentrations below LEL in the battery space. Ventilation is a relatively slow process, and works only when the gas release rate is small enough. If the gas release rate is above a certain mass flowrate, then a flammable gas might form, and an explosion can follow.

If the battery produces enough gas to create an explosion, and the ventilation system is not able to dilute the gas, then venting panels or weak walls towards safe areas need to be installed. This is considered further in 0the section pertaining to explosion venting panels.

A strategy for ventilation and fire protection when temperatures above warning levels are detected is needed. Flammable off-gases will be generated from the battery electrolyte solvents if cell temperatures go above certain values. Adequate ventilation in the battery space can contribute to manage this risk. If the battery damage might cause a flammable atmosphere in the battery space outside the module, an additional emergency, non-sparking, mechanical exhaust fan and emergency inlet direct from open air may be required.

The communication of alarms and detection of sensor failures must also be evaluated. It is important that the system for detection of flammable gases is reliable and fast. Relevant requirements need to be identified. The ventilation fan for extraction of gas from the battery space (or module) should start automatically on flammable gas detection or unacceptable temperature. In most cases, the flammable gas is expected to be lighter than air due to the temperature and composition. Detectors need to reflect the situation for the specific system (e.g. placing detectors high in the room to detect light gases). The gas composition analysis should be used to decide the density of gas and provide input to gas detectors placement depending on whether the gases are expected to be lighter or heavier than air.

Fire detectors should close the incoming and outgoing air ducts automatically. This can aid suffocation of the fire.

Gas and fire detectors should be selected carefully to avoid detection by “wrong type of gas” as this might in the worst case increase the risk instead of reducing it.

The following is an example of a ventilation and fire protection strategy:

1. Electronically disconnect the battery system.
2. Increase battery cooling as much as possible.
3. Ventilate battery off-gases to outside the ship, as long as there is no fire.
4. If fire breaks out, shut down ventilation and activate fire extinguishing system.

Key issues are to quantify the formation of flammable gasses and how the gasses are likely to disperse.

Explosion risk

The risk of an explosion need to be assessed based on the gases that might be emitted (section 5.1). This includes analysis of the generated quantities and resulting gas concentrations as these gives the design basis for battery space. From a safety perspective, key issues are to determine how likely it is that flammable gases will be detected and the expected effectiveness of ventilation with regard to keeping the gas concentrations below the LEL limits (as identified in the battery manufacturer's safety description). The likely scenario development including number of cells affected and possibly simultaneously venting gases need to be described.

Assessment procedure for explosion safety

The steps of a general procedure to design against explosions and show that explosion safety is acceptable are described in this section. More details of the points are described in the sections following this one.

1. First the battery space must be designed with the power needs, number of battery modules and available space.
2. The design of the battery space gives necessary input to the explosion safety assessment where the main design parameters that influences explosions are as follows:
    a. Volume of battery space
    b. Type and size of batteries. Information from vendor/experiments: Composition of emitted gases, total mass emitting from the batteries in an accidental situation, gas emitted as a function of time (kg/s) and duration of gas emission (s)
    c. Design pressure of walls and decks in the battery space
    d. High temperature or gas detection systems that automatically starts emergency ventilation systems
    e. Emergency ventilation system to mechanically vent out gases from the battery space during gas emission.
    f. Overpressure venting panels that releases upon increased pressure. Weight and opening pressures for the venting panels.
3. The first step is to calculate the possible gas cloud volume assuming the gas emitted will form an ideal mix of stoichiometric gas. The resulting gas cloud size is the worst case scenario. Walls can be designed to withstand this worst case scenario as described in section 5.1.4. If a lower design pressure is wanted, the procedure described here should be followed.
4. If the gas release is not instant, the gas might disperse unevenly through the available space over a longer period of time. This can be assessed by dispersion modeling where all the available gas will be considered to calculate the flammable gas cloud size development in the available space over time. Here, the ventilation of the battery room will help to dilute the gas and remove it from the room.
   If the ideal stoichiometric gas cloud size is too conservative and not possible to design for, it is recommended to perform a CFD dispersion modeling in order to decide the size of the flammable cloud. The CFD model should consider the mechanical ventilation in the room (sources and sinks), gas leak rate versus time, gas composition etc. The CFD model can then be used to investigate reasons for large gas clouds and suggestions can be made on how to reduce cloud sizes (e.g. avoid stagnant areas in the room, etc.). Such CFD modeling should be performed with a recognized CFD code and by trained experts.

5. Calculate the possible explosion pressure using linear relation between pressure and equivalent stoichiometric gas cloud filling fraction.
6. If the calculated explosion pressure is higher than structure design pressure, then decide if the size, opening pressure, weight and release time of the releasing venting panel is sufficient. It is important to also include the correct pressure buildup time in the calculations. This should be performed using a recognized CFD model that can handle explosions and trained experts.
7. If calculations of explosion pressure and pulse duration with release panels included show that the pressure is lower than the design pressure with the appropriate pulse duration, then the design is sufficient to handle possible explosion loads.
8. If design is not sufficient, redesign should be performed. The following can be implemented:
    a. Higher design loads for explosion on walls and decks
    b. Larger release panels and opening at a lower pressure
    c. Improved ventilation that starts on gas detection
    d. Increase size of battery room.
    e. Deluge can be released on gas detection. This is shown to help for relatively high explosion pressures /7/. For lower pressure, deluge may increase the pressure slightly. Hence the effect of deluge on explosions has to be shown to help before it is installed as a mitigating measure for explosion.

Explosion risk assessment

Explosions in enclosed rooms can result in unacceptable pressures provided the cloud size is large enough relative to the battery room. The cloud size resulting from a battery failure situation is therefore of major importance for the final explosion pressure. In case of an ideal mixture between flammable gas and air, the maximum pressure generated by an explosion within the room can be up to 6-8 barg /8/. The pressure buildup time is quite fast for small rooms, and a room with a volume of 20 m^3 can typically give a pressure increase time of approximately 100 ms. After the pressure has increased, it will be reduced depending on any openings in the walls where gas can escape. Due to the rapid increase in the pressure during such explosion, any relieving panels that are designed to open during and explosion need to be quick enough to open well before the peak pressure is reached.

The amount of gas and the flammable cloud size is established based on the battery failure mode and gas dispersion process. A simple linear relation between the filling fraction of stoichiometric gas and the explosion pressure can be used to estimate the possible maximum pressure from a gas explosion inside an enclosed room. The maximum pressure is 6-8 barg if the mixture between gas and air is near stoichiometric and filling the entire room. The pressure is then linearly decreasing for smaller filling fraction, e.g. with a 50% volume with a stoichiometric gas and the rest is air, and then the maximum pressure is 3-4 barg.

The design load of the walls and decks in the battery room must be established based on the structure design documentation. The explosion load will act on all 6 surfaces of the battery space at approximately the same time.

If the design accidental load of the walls is lower than the pressure that comes from a possible explosion, then some mitigating measures must be implemented that can reduce the peak pressure. The most effective design measure is to have a wall or section of the wall that is designed with low release pressure.

In order to show that the relieving panel is designed appropriately it is necessary to use an advanced CFD model such as FLACS to be able to capture the rapid dynamic behavior of the explosion and the panel. It is hence recommended to use a CFD model in cases when the potential explosion pressure is higher than the design pressure of the walls.

The pressure buildup time also need to be considered when applying the explosion load on the structure. If the natural period of the structure is similar to the duration of the explosion, then amplification factors may apply. DNV GL RP C204 provides structure response calculation guidelines for dynamic explosion loads.

The strength of walls and decks vary significantly depending on the plate thickness, distance between girders, and supporting beam dimensions.

Ventilation effects on safety

The fire and explosion risk depend on the ventilation of the room where the battery is located. If gas is released from batteries, it will mix with surrounding air and create a flammable region in the vicinity of the battery as described in the next section. If the ventilation is high, the gas will be diluted faster and create a smaller flammable cloud. If the ventilation is low or zero, the gas will mix slower and can create a larger flammable cloud. There are three different ventilation and venting systems that needs to be implemented or considered in the battery room:

1. Normal ventilation to provide cooling of batteries. The design for cooling need to be considered by manufacturer, and need to be accounted for when assessing gas dispersion from a battery.
2. Ventilation through ducts with inlets and outlets to outside air. The purpose of this is to vent out flammable gases and smoke.
3. Explosion venting panels to vent out during an explosion.

Descriptions of the two last systems are given in the following sections.

Ventilation to vent out flammable gases and smoke

The purpose of this ventilation is to remove flammable gas and smoke generated by gassing from the battery.

When a gas leak is detected without a fire, the ventilation to outside area should be started immediately in order to remove the gas out from the battery space. The class requirement indicates a ventilation rate of minimum 6 ACH. However, the ventilation rate can be as high as possible considering the vent ducting and limitation on air flow speed. This requires at least one inlet and one outlet from the room. For use when potentially flammable gases are detected, the fan needs to be spark free, to avoid ignition. Alternatively, an assessment of the gas volume in various failure scenarios may show that a spark free fan is not necessary.

Gas detectors should be installed to detect flammable gases as quickly as possible. Alternatively, or in addition to gas detectors, detection of cell temperature above the safety level should also start the fan.

Gas dispersion studies can be applied to estimate the size of flammable gas clouds and this can be used to decide how to locate the gas detectors needed to reduce the risk of explosion. According to class requirements, the gas concentrations at which actions should be automatically initiated are 30% and 60% LFL for battery disconnect and start of fan, respectively.

The philosophy for operation of the ventilation system in case of gassing and fire need special consideration based on the characteristics of the battery system. Some batteries produce O_2 as part of the emitted gases, and such aspects need to be considered. Stopping the ventilation will unless O2 is generated normally be expected to contribute to suffocate the fire. However, there might also be good reasons to extract hot gasses and combustion products out from the battery space. Therefore gas and fire modelling is advisable to provide input to determine the safest strategy.

The air flow in the battery space can be simulated with Computational Fluid Dynamics (CFD) in order to optimize design of the ventilation system inside a battery room before any leak occurs. Results from CFD can then be used to identify where stagnant air and re-circulation zones exists. The ventilation in the room should be designed to provide as uniform flow as possible in order to avoid gas cloud buildup. The direction of the air flow that starts on gas detection should be the same as the general flow direction before the leak starts. Since the gases from the batteries are usually warm and lighter than air, the inlet should be at the bottom, and outlet near the top since this is the natural flow of the buoyant gas.

Explosion venting panels

The purpose of explosion venting panels is to release the pressure in case of an explosion in the battery space. Such panels should be located so they vent out to a safe area, preferably on a vertical wall. Explosions can build up the pressure within 1/10 of a second, hence, it is important that the panels releases quickly and are light. The releasing pressure should not exceed 0.05 barg. Explosion venting panels can also vent out to other spaces next to the battery space. It needs to be shown that the volume of the neighboring space is sufficient to reduce the explosion pressure to acceptable levels and that the consequences to these spaces are acceptable.

It should be documented that the vent panes reduce the pressure below the design pressure of the battery room surfaces. This can be documented by performing CFD simulations of explosions including the releasing panel in the simulations.

The design pressure of the battery room surfaces needs to be determined and documented. It needs to be shown that the design pressure is higher than the possible explosion pressure in the room, or that the consequences still are acceptable.

Fire Risk Assessment

Both gas development and fire and explosion risk are closely related to thermal runaway. Another aspect with fire risks are that there might be an external fire outside that may affect the batteries. With respect to rooms adjacent to the battery space, normal good quality fire detection and fire extinguishing should be sufficient in order to prevent a fire spreading from adjacent rooms to the battery space.

With respect to thermal events originating in the battery space, early detection and increased cooling power will help to keep any fire under control. Conventional smoke detectors and a water based fixed fire extinguishing system may be required unless the safety assessment dictates otherwise.

The following safety strategy with respect to a battery fire is anticipated:

1. Electrical and thermal control through BMS without option for manual override of safety functions.
2. Cell thermal runaway shall be kept confined at lowest possible level, therefore:
    a) The design of a module shall inhibit propagation from cell to cell.
    b) If 2a) cannot be guaranteed, the module outer surface shall not exceed a critical temperature level of approx. 130 ºC during a thermal event. No flames shall be visible.

c) If 2b) cannot be guaranteed, the battery space must inhibit propagation between modules as well as surrounding materials catching fire.

3. Fire within several modules must be assumed to be out of control. Vessel evacuation cannot be excluded.

Strategy with respect to fire outside the battery space:

1. Any fire shall not lead to temperature above 70°C within battery modules for more than 30 min.
2. If the cell temperature has exceeded the battery manufacturer's maximum temperature, the battery system needs to be evaluated by the battery supplier before it can be put back into use.
3. Fire classes applied on walls, doors etc. shall protect the battery system to withstand fires for the needed duration (indicating that the doors and walls must be able to withstand an external fire).
4. If possible, decrease SOC to reduce the risk for a thermal event in the battery system.

As a general consideration, fire extinguishing medium, either water mist, (heavy) foam, or other water based mediums should be considered to provide cooling of the battery.

External fire risks

External fires pose a potential threat to a battery installation. Fire integrity of the battery space has to be properly addressed based on requirements in the applicable rules and standards as the ones mentioned in 4.3.

In addition it is recommended to ensure that in case of external fire or heating to the battery space, escalation of the fire to the battery room is avoided, at least in the period before the ship is evacuated.

If a battery space is located next to areas where the fire risk is high, an assessment of the need for fire rating walls or decks between these areas is recommended.

The risk of fires in rooms adjacent to the battery space should be evaluated. In case of fire risk in the adjacent rooms, it is recommended to establish the fire load from these rooms (with a heat flux and duration). This way, it can be shown that the walls or decks bordering the battery space can withstand such fire loads.

Other threats could be the risk of puncture of a cell due to operations not directly related to the battery system (overhead crane operations etc.). The location of the battery space on board the vessel has to be carefully considered in order to reduce the risk of external events posing a danger to the battery system. The class rules (ch. 4.3) states that the battery space cannot be placed forward of the forward collision bulkhead.

Loss of essential or important services

The safety assessment shall also consider the risk of losing essential or important services due to battery system failure, and consider actions to mitigate these risks. Elements to address should be to avoid placement of essential and important equipment in the battery space including piping and wiring to these systems.

APPENDIX B. BATTERY SYSTEM AND RELEVANT FAILURE MODES

The battery system consists of one or more battery strings including all required systems for the intended purpose. This chapter outlines recommendations made from the FMECA analysis and failure modes identified. Figure B.1 below illustrates the battery system and sub-system definitions applied.

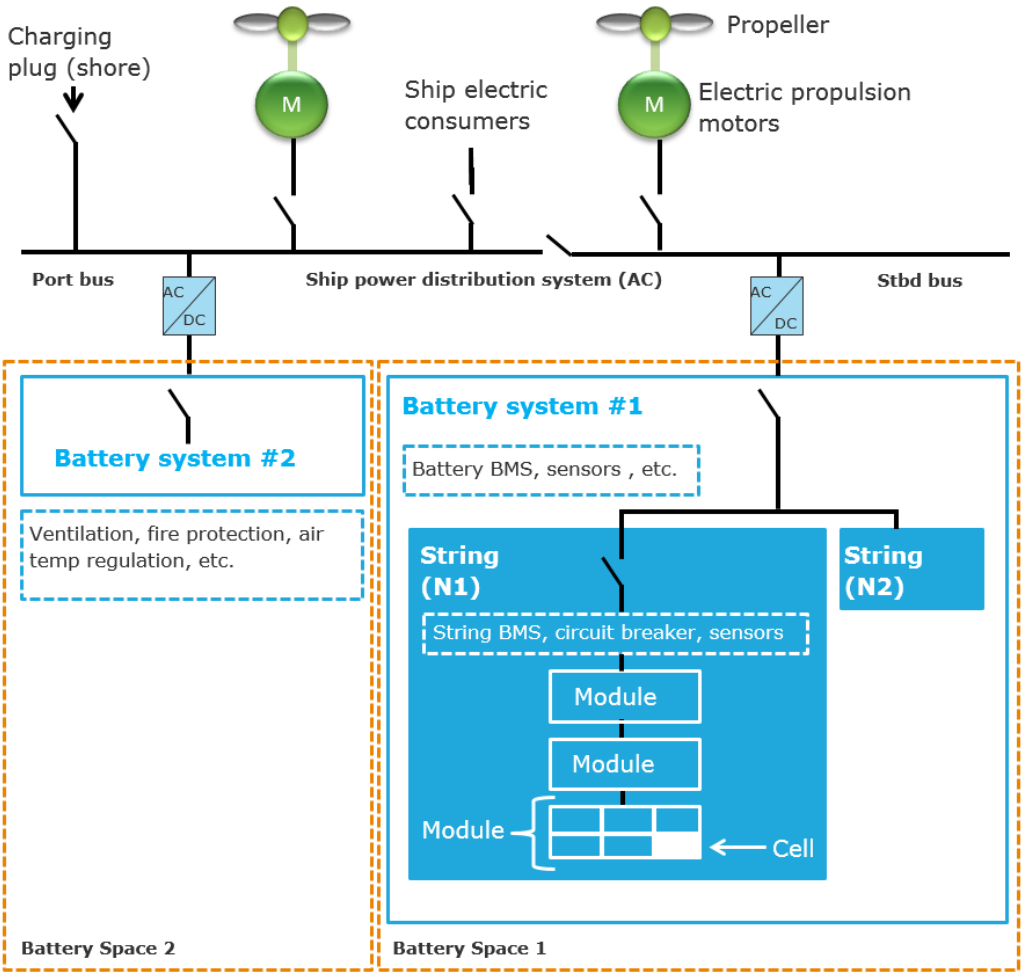


Figure B.1. Battery System and related sub-systems

Cell-Based Failure Modes

This sub chapter described possible process deviations on cell level, as a supplement to the failure modes detailed in chapter 5.1.1.

High Impedance

If a cell or cell connection has high impedance it will result in increased heat production during operation. If one cell is exposed to higher temperature, the impedance growth in this cell will be higher than the impedance growth for cells at a lower temperature. This generates a positive feedback effect with the potential to severely affect the life and performance of the battery. If the heat production is high enough this can also have severe safety implications since thermal events can be initiated.

To check the AC impedance of individual cells prior to assembly into battery modules, the standard method is to use a milliohmmeter implementing a 1 kHz AC test signal for precise measurements of extremely low resistances. This procedure is usually an inline test to check the supplier quality. It is important to keep in mind that this is an AC impedance test. For the usage of the batteries in a battery string, the DC impedance is usually more important. The DC impedance will also incorporate capacitive elements originating from electrochemical reactions and diffusion processes. Testing the DC impedance of at least modules prior to commencing usage of the battery system is necessary.

The impedance in a cell or a group of cells can be calculated by Ohm's law by dividing the voltage by the current, provided the voltage and current are measured at the same time. Then the impedance of one group of cells can be compared to the impedance of another group of cells.

For batteries with minimum two parallel strings of cells or modules it is important to measure the current in each string because this way the string impedance can also be calculated. Further the string impedances and/or the current going through each string can be individually compared to identify impedance abnormalities.

In all cases the BMS should keep track of the DC impedance (resistance) of the system and preferably the DC impedance of all cells connected in series in the battery system. This information is important to determine safety performance and battery life.

Insulation fault

Pouch cells have a soft exterior surface which needs to maintain its electrical insulation over lifetime. Particles on the surface can damage the outer layer via persistent wear, e.g. under vibration and over time. A pressurized assembly line room with filtered air is recommended to mitigate contamination of particles.

Prismatic/cylindrical cells with a solid metal or plastic can are not as sensitive. However, depending on the joining method and other operations during assembly (circuit boards), a clean and dust-free environment is also recommended.

Also refer to description of insulation fault on module level, below.

Electrolyte leakage

Leakage of electrolyte is a possibility, especially from pouch cells. Electrolyte can have a sweet smelling organic solvent odor. Typically the electrolyte contains lithium hexafluorophosphate ($LiPF_6$). The interaction of water or water vapor and exposed lithium hexafluorophosphate may result in generation of hydrogen fluoride (HF) gas and subsequently corrosion products. Contact with battery electrolyte may be irritating to skin, eyes and mucous membranes. Fire will produce irritating, corrosive and/or toxic gases. Fumes may cause dizziness or suffocation. In addition small amounts of phosphoryl fluoride may be formed. Phosphoryl fluoride is a toxic where short exposure could cause serious temporary or moderate residual injury. Similar compounds in this category are chlorine, liquid hydrogen, and carbon monoxide.

Solvents within the electrolyte are often variants of ethyl carbonates. Evaporation of these carbonate solvents leads to flammable gases that can create explosion risks when the lower explosion limit (LEL) is reached. In case of electrolyte leakage, proper ventilation is important. Avoiding trapping of the most volatile gases such as hydrogen and methane, is important in order to avoid severe consequences such as fire and/or explosion. Cells leaking electrolyte may produce gases lighter or heavier than air. Some volatile and hot gases will rise towards the ceiling of the battery space. It is therefore recommended to have an air intake placed fairly low and a ventilation outlet placed as high as possible in the battery space to avoid trapping of volatile gases. Further the ventilation system should be designed to ensure sufficient air exchange to minimize the risk of any concentration exceeding the lower explosion limit (LEL).

Hydrogen fluoride is extremely corrosive and when formed it will most likely initiate further corrosion in the surroundings. For pouch cell systems, there is a high risk of a corrosion reaction initiating further electrolyte leakage from adjacent cells if electrolyte is allowed to come in contact with the aluminum pouch cell liner on one or more adjacent cells.

Electrolyte leakages may cause accelerated corrosion and should be detected via electrical insulation measurements provided that the battery system insulation measurement strategy is designed to detect such leakages. In the case of undetected breaches in cell packaging, leaking and evaporating carbonate solvents can be detected with sensors sensitive to these species. Other detection methods can be increased self-discharge rate, loss of power, increased impedance, detection of organic compound fumes etc.

In case of electrolyte leakage, the battery manufacturers MSDS should indicate methods for cleaning the spill. Pouch cells exposed to electrolyte should be permanently taken out of use as cells may have experienced damage that could be very difficult to detect.

Other cells than pouch cells may also leak electrolyte and proper module design is extremely important in order to prevent such leakage. For cell types where the cell can does not have any polarity, it is important that the can is electrically insulated from the rest of the system.

Typical root causes for electrolyte leakage are cell packaging in electrical contact with battery casing. Pouch cells have several additional potential root causes for electrolyte leakage. Examples of such root causes are improper handling of cell flanges, improper handling of battery cells during manufacture as well as cell pouch liner polarization for instance from poor design in combination with high voltage insulation measurements.

Once one cell starts leaking and the electrolyte from this cell comes into contact with other cells, there is a strong likelihood that the other cells also will experience electrolyte leakage. This is particularly likely for pouch cells where the leaked electrolyte comes into contact with the cell pouch liner. Electrolyte leakage can also cause shorts across cell or module electrical connections, resulting in additional safety risks.

The manufacturer of a battery system should have a quality regime in place that ensures proper handling and manufacturing. Elements such as traceability, consistent use of non-conductive tools, environmentally controlled assembly and production spaces and proper use of special protective equipment etc. are important. Relevant results from in line testing should also be stored for at least the lifetime of the battery. Such a quality regime may be subject to evaluation if the manufacturer decides to apply for a general type approval if the batteries.

Module Related Failure Modes

This sub-section outlines the relevant failure modes which take place at a module level. As outlined in Section 3.5, the battery module plays a key role in preventing propagation and cascading failures.

In addition it provides many active roles with regard to safety and failure mode protections – these are discussed in detail below.

Battery Management System Control Failure

A properly designed battery management system must, at least, have the following features:

- Control discharging and charging of the battery by setting limitation and communicate these to the charging system
- Protect against overcurrent, over-voltage and under-voltage
- Protect against over-temperature
- Control cell balancing
- Monitor cell voltage, temperature and battery string current, and display maximum, minimum and average cell values
- Calculate SOC and SOH and communicate these values to higher level control systems if needed
- Provide alarms and shutdown signals for all of the above

Short circuits

The following can be considered recommended guidelines to avoid short circuits or to isolate them. It should be noted that other measures may have to be taken depending on the specific design:

- Basic fusing strategy should follow a cascade, so that an external short circuit causes the main fuse to blow (component easiest to exchange).
- All fuses need to be tested and certified against maximum system voltage to avoid arcing.
- If a module does not have specific fusing capabilities, the supplier needs to demonstrate the safety by an external short circuit test at different voltages and temperatures (see available standards UL/UN transportation, IEC62281/1).
- In order to avoid short circuits, each exchangeable unit (module) must have preventive design measures against accidental shorts (screwdriver etc.) and intrusion of potential conductive particles.

The positive and the negative terminals should not protrude from the module casing. The module casing can include non-conductive, non-removable terminal protection in cases where the terminals are protruding from the module surface.

Temperature sensor failure, voltage sensor failure

Strategy for sensor configuration and reaction to sensor failure:

- Voltage sensors to be installed for every cell or parallel cells in a series of connected cells.
- Temperature sensors must be placed in such a way that temperature differences between any cells exceeding 5˚C for more than 5 minutes are detected.
- The density of temperature sensors need to be high enough to enable safe battery operation, even with one failed sensor per battery module.
- To prevent safety or other critical issues, voltage sensors require some form of redundancy.
- Temperature sensors also need some redundancy.
- If there is a failure in a voltage sensor, it is possible to further operate the battery provided that the cell voltage(s) for each of the cells with failed sensors can be calculated from other measurements (such as module level).
- The accuracy of the voltage measurement needs to take into account safety, energy content estimation and balancing requirements.
- Inadequate design and/or location of battery voltage or temperature sensor wires can pose a fire hazard. Such sensor wires should have a suitable cross section to avoid the possibility of excess heat

buildup in case of a short circuit going through the sensor wires. In addition a proper separation of the different sense wires on the BMS is required.

Insulation fault

- The insulation resistance should be as a minimum:
  - 1 MΩ for Un < 1 000 V
  - (Un/1 000 + 1) MΩ for Un >= 1 000 V
- Poor insulation can result in premature aging of battery systems and - in extreme circumstances - a safety risk.
- Insulation testing in itself can, under certain conditions with certain designs, provoke insulation faults if superimposition of DC voltage is used for insulation measurements as is normal for AC systems.
- For DC systems with high system leakage capacitances, a DC method may not be reliable. Other methods using for instance Non DC signal for measurements are therefore recommended.

Loss of cooling

The battery system shall be operable at minimum requested discharge rate (e.g. needed during limp-home mode, steering speed) without external cooling in case the cooling system is needed under normal operation conditions.

String Electric Integrity

A string is the smallest unit with same voltage as the system level. This is the smallest unit that can be electrically isolated, unless internal module design provides some sort of internal isolation of cells. Depending on the system architecture, each string can have internal relays/contactors which can interrupt main power connection. The string architecture shall foresee, in case:

- the string does not contain one or several relays: an exchangeable fuse and a main power connector with a minimum rating of IP20 in unconnected state (touch proof)
- the string does contain one or several relays: the main power connectors might have an integrated High Voltage InterLock (HVIL) contact (last make/first break type contact) which opens the relay/relaysLarge plastic parts (above 200 g weight) should be material marked, e.g. CE marking.

Moreover, the string should comply with the following:

- All plastic parts within a battery system should preferably be of low-smoke zero halogen material (e.g. no PVC cable coating). Reference is also made to offshore material standards.
- Unauthorized access to the internals of battery modules must be inhibited as far as possible.
- The main components of a battery system should be protected against unauthorized mechanical access (e.g. by tamper-proof screws or crimp seals).
- All components of the battery system shall be properly marked and reflect their specific danger potential. Relevant operators and personnel shall be trained accordingly.
- The responsible operator of a battery system shall have a competence requirement scheme for construction, operation and maintenance of the system.

- The battery strings shall have sufficient protection mechanisms against intrusion by software and unwanted calibration access to the battery system.
- The battery strings shall include contactors on both + and - sides. The rating of the contactors shall include sufficient margin with respect to the maximum expected current during normal operation.
- If the electrical architecture of a string contains independently controllable parallel strings, each single string shall include independent current measurement.

The battery system shall be able to detect major and potentially dangerous connector high impedance and shall have implemented adequate warnings and/or failure messages for the rest of the system in case such failure is detected. Large impedance differences in parallel strings will cause different current distribution in the strings.

The battery system should include segregation possibility of its cooling system in case of cooling medium leakage and given the medium is a liquid which imposes potential damage to the system or its environment.

Full Battery System Considerations

This sub-section outlines the relevant failure modes on a system level.

High level sensor failure

All battery related control systems shall have access to and make use of data from all relevant sensors included in the battery system which are important for critical controls.

Voltage and temperature imbalance

Each lithium-ion battery cell will have its own individual self-discharge rate. The self-discharge rate is determined by the properties and purity of materials used in the cell. The level of contamination in the electrolyte and electrodes is particularly important. The self-discharge rate will depend on temperature and battery cell age. In certain cases the duty cycle experienced by the battery can influence the self-discharge rate. The battery management system may contribute to unequal self-discharge rates between cells or groups of cells.

In order to maximize battery life expectancy and be able to utilize the full capacity of the battery system, a battery balancing system should be included. Large battery systems will have a cell balancing system included in the BMS. This system could be of passive or active type.

The principle behind a passive balancing system is that bleed resistors are used to remove energy from the cells with the highest state of charge. Usually the bleed resistors are activated only at high states of charge. With an active balancing system, energy is transferred from cells with high state of charge to cells with low state.

All cell voltages shall be monitored and the difference in cell voltage should not exceed a specified limit.

- For a fully balanced battery system, all cell voltages are within a specified limit.
- The available energy is limited by the cell with the lowest voltage. In an imbalanced system, this will cause reduced capacity.
- The SOH and SOC should be compensated to account for the capacity loss due to any imbalance.

When temperature imbalance is considered, it is important to consider that virtually every battery control parameter is temperature dependent. Variation in temperature across the battery string will therefore influence performance, safety and expected life time. Individual temperature difference should therefore be monitored. Usually the maximum cell to cell temperature difference is specified and it is often recommended that a maximum difference of 5 degrees Celsius should not be exceeded during normal operation.

Degradation and reduced battery life

The key to meet the targeted battery life is a good understanding of the actual load cycle and a battery system optimized for the application. The key elements in such an optimization is a good understanding of the cycle and calendar life of the cells used, the system set up including charge and discharge patterns, the thermal management of the string and the way the BMS is set up with regards to upper and lower voltage limits, cell balancing and other key parameters.

All batteries degrade as they are used. A good understanding of the degradation for actual application is important for sizing the battery system. If the targeted operational life is 10 years, the expected degradation over this period must be accounted for. Good degradation models are crucial for such a calculation.

An important factor to a long life of the battery system is to keep the cell temperature within the optimal range, usually 20 - 30^0. A good degradation model calculates the cell temperature under different cooling conditions. To achieve an optimal battery size for a given application – load profile, cell type and battery cooling system and energy losses in the system needs to be evaluated.

Contactor does not open when required

The battery string/system shall include contactors on both + and - sides. The rating of the contactors shall include sufficient margin with respect to the maximum expected current during normal operation.

Contactor does not close when required

If the electrical architecture of a battery system contains independently controllable parallel strings, each single string shall include independent current measurement.

The BMS of a battery system shall be able to detect a non-closing relay/contactor.

Reverse polarity protection

It is recommended that battery system safety tests include testing of reverse polarity of control unit supply voltage and mechanical coding of battery terminals.

Emergency disconnection

It shall be possible to disconnect the battery system in an emergency situation. This should be done by implementing an emergency shutdown circuit that disconnects the battery contactor/breaker. This emergency shutdown must be arranged as a separated hardwired circuit and, depending on the application it should be possible to shut down the battery both locally and from the bridge.

Consumers – Electrical AC and DC distribution

Figure B.2 below shows the sub-systems included in Consumers.

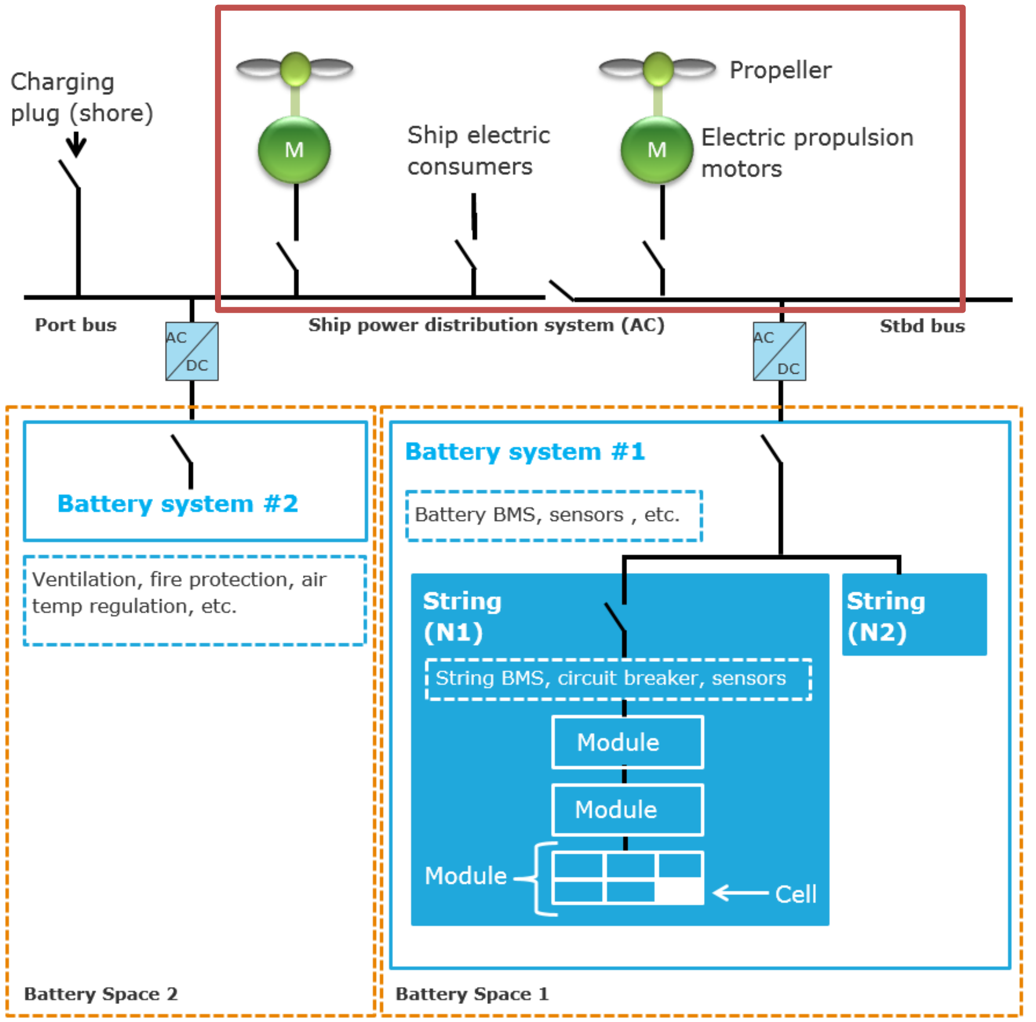


Figure B.2. Sub-systems for Consumers.

The Redundancy configuration of battery installations shall be such that power blackout of the vessel is prevented. BMS/PMS shall provide alarm when electrical currents are inconsistently high.

Discrimination analysis of breaker selectivity in electrical distribution system shall be performed.

Automation – Energy Management System

This chapter described issues relevant to the energy management system and automation.

Estimation of energy fault

Whenever possible, sophisticated systems should be used to make consistency checks and to perform sophisticated, non-critical decisions. These systems should assess the remaining energy and remaining life of the battery system. This is also addressed in the DNV GL class rules.

- The SOH, normally calculated in the BMS, must be used to calculate and update available energy and available power.
- Available energy (SOC) estimation and display is required for accurate planning on the part of the captain as well as the ship PMS. This is also vital to avoid a scenario of overcharging or overdischarging a battery.
- The power estimation needs to follow a similar approach.

Calibration/reference point: A fully charged and balanced battery system where the internal concentration gradients have had time to relax, is at 100% SOC.

To avoid unnecessary questions and to add some safety margins the displayed SOC can be adjusted to be different from the real SOC when the real SOC is above 90% or below 10%. The voltage during operations and charging can be used as a quick check to ensure that the SOC estimate is within reasonable limits. This is particularly true for operations with a non-constant duty cycle.

Power Management

The automation system should be designed in such a way that the battery temperatures are kept within specified limits. This should be done by limiting:

Maximum charge and discharge current rates.

Maximum and minimum battery voltages, i.e. over charging and excessive discharge.

Power input

This chapter describes issues related to power input to the battery system. This typically includes:

- On-land distribution and shore connection
- Engine and generator
- Charger (including AC/DC)

For applications operating on “battery power only” fast charging feasibility will be critical.

The charging system and other relevant systems shall detect the connection to shore power and activation of propulsion shall be inhibited in this case. Note that some applications will need propulsion power even when connected to shore power, in those cases safety measures must be taken to avoid unintended un-plugging of the charging interface.

There shall be no flammable materials close to shore power connector in order to prevent fire propagation from connector to environment and vessel.

The charging system and shore connection shall include temperature sensors in order to detect high impedance and heating in an early stage.

The mating process of the shore connection shall be preferably automatic. If not, a risk assessment for involved personnel shall be done.

The charger should be designed in such a way that too high charge currents and voltages are avoided.

APPENDIX C. CLASSIFICATION

BATTERY RULES

Background:

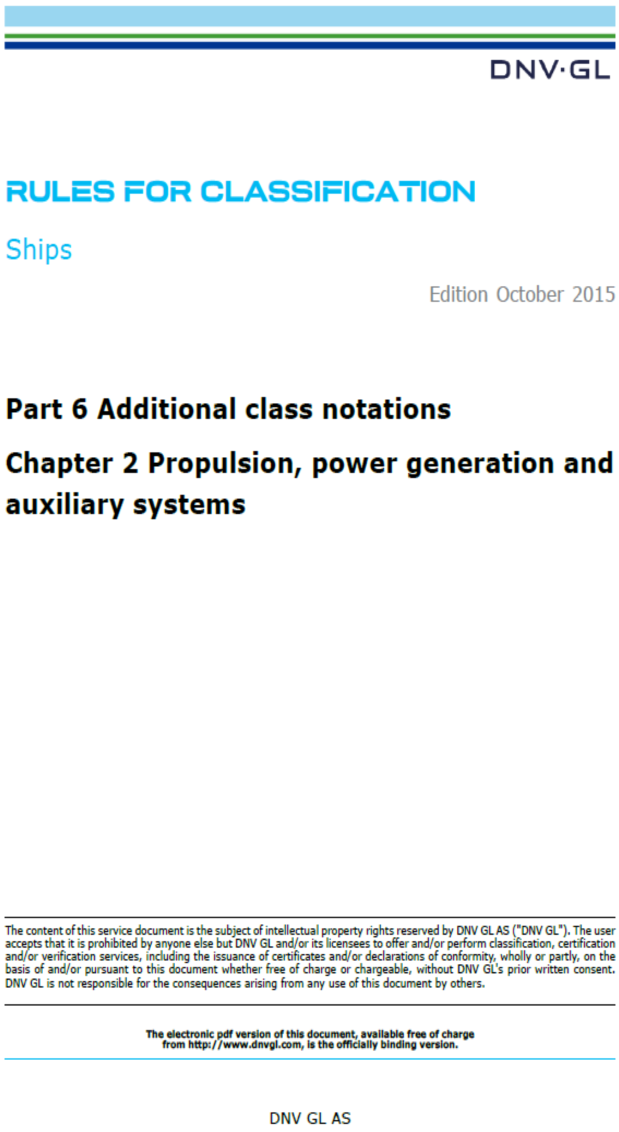
Due to the new battery technology, where it is possible to use batteries as a part of the propulsion energy for vessels it is possible to make hybrid battery solutions and "pure" battery driven vessels DNV introduced class rules for battery powered systems. The rules have been official from 1. January 2012. The class rules for battery powered systems were updated in October 2015

The requirements cover:
- Safeties of the battery installation with special focus on lithium batteries.
- Battery systems used for propulsion
- Requirements for certification of the batteries.

Class notation
Battery(Safety) notation covers the safety aspects of a battery installation were the aggregate capacity exceeds 50kW. Battery(Power) notation includes additional requirements when the batteries are used for propulsion or can be considered a main source of power.

Class rules
The rules can be found on the following link:

[DNV GL Rules for Battery Power]


DNV·GL

RULES FOR CLASSIFICATION

Ships

Edition October 2015

Part 6 Additional class notations

Chapter 2 Propulsion, power generation and auxiliary systems

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DNV GL AS

CERTIFICATION

For a DNV classed vessel it is required that the batteries shall be certified for each vessel. Requirements for the certification are given in the Battery Power class rules. In addition to this, DNV offer a service for Type Approval of battery systems. This type approval will on a generic level verify that the battery system fulfill the requirements in the DNV class rules including applicable type tests (safety and environmental tests). The type approval does not replace the "case by case" certification, but will limit the scope of the "case by case" certification.

APPENDIX D. BATTERY SIZING AND DEGRADATION ANALYSIS

When it comes to determining the required size of battery for a given application, many complex factors come into play. Because a battery will unavoidably experience degradation during its lifetime, and because operation at the extremes (top and bottom) of its State of Charge (SOC) range will accelerate degradation, batteries must be oversized for a given application. A smaller battery is more cost effective, while a larger battery is better able to maximize benefit or power a ship a longer period of time. For a given application, a larger battery will also experience less degradation in performing the same operations. Sizing is the basis of the question of capital cost (CAPEX) compared to revenue, or payback time, and thus determining the size of the battery is the central factor in a feasibility or techno-economic study. Furthermore, every battery is different. Even batteries of the same type of lithium ion chemistry (for example NCM, or LFP) may exhibit significantly different characteristics. Thus, it is important to take into account factors and data specific to the battery system offered by a given vendor. This also highlights the fact that each battery may be stronger in certain areas than another (for instance: temperature resilience, cycle life, high power capability, energy density) and the best result will be achieved by ensuring the most appropriate battery technology and system design is used for a given application.

Determining the most appropriate battery technology for a given application is a complex question depending on a large number of interrelated factors including temperature, sizing, use profile, control system, economics, as well as the chemistry and manufacturing of the battery itself – an overview of the key components is presented in Section 3.2.2. DNV-GL has engaged in both experimental and analytical efforts to understand these aspects, to be able to provide guidance and insight into different system design and sizing considerations. Batteries are sensitive both to the relative power level that is used (c-rate) as well as the energy throughput. A larger battery may be needed to compensate for one of these factors more than the other, or a given chemistry may be able to provide more economical benefit in this regard.

An example of how this can vary for different batteries – all of NCM chemistry – is shown in Figure D.1.

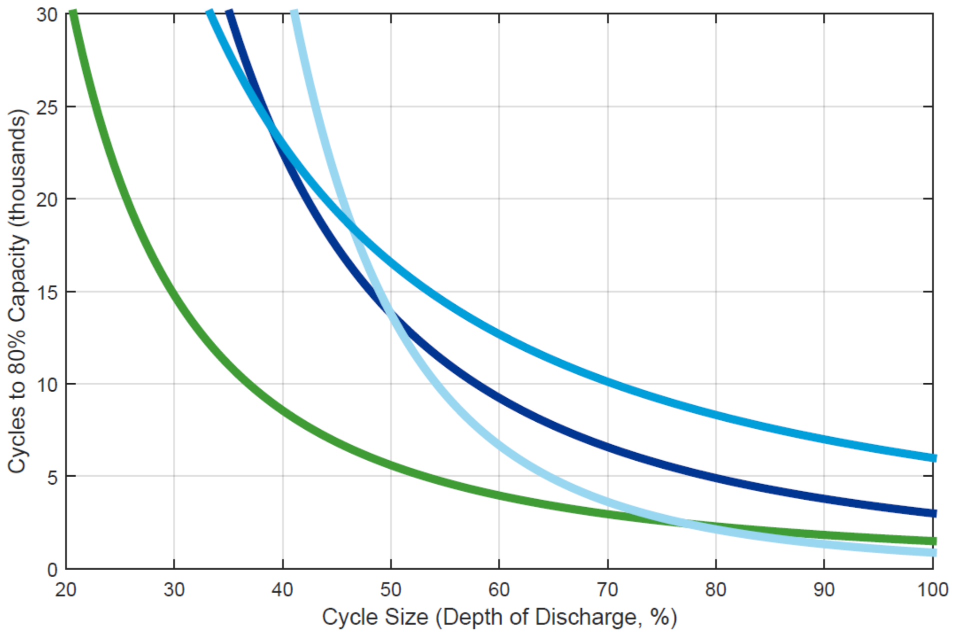

Figure D.1 Batteries are able to perform more cycles when only a small portion of the total energy is used in each cycle – a nonlinear relationship that varies substantially between different battery chemistries and manufacturer.

The relationship shown in the figure above is a snapshot of the effect of one subset of parameters on battery service life. Inevitably, as we change one aspect of a battery design, it will impact some other aspect. Thus, the key is to evaluate the full spectrum of these parameters simultaneously – in a manner that is relevant and specific to the application under assessment. This is the capability and purpose of the battery sizing and technology selection tool BatteryXT. With its main interface window shown in Figure D.2 below, BatteryXT is designed to perform detailed analysis of the specific load profile which the battery is to be used for, and enable identification of operational risks relative to the battery's capabilities as well as factors that should be taken into account with regard to sizing procurement. This process can then be done for multiple systems in order to provide some guidance on the best fit technology for a given application. This allows engineers to determine the key tradeoffs of system design, and help customers make the hard decisions necessary for ensuring adoption of successful systems.

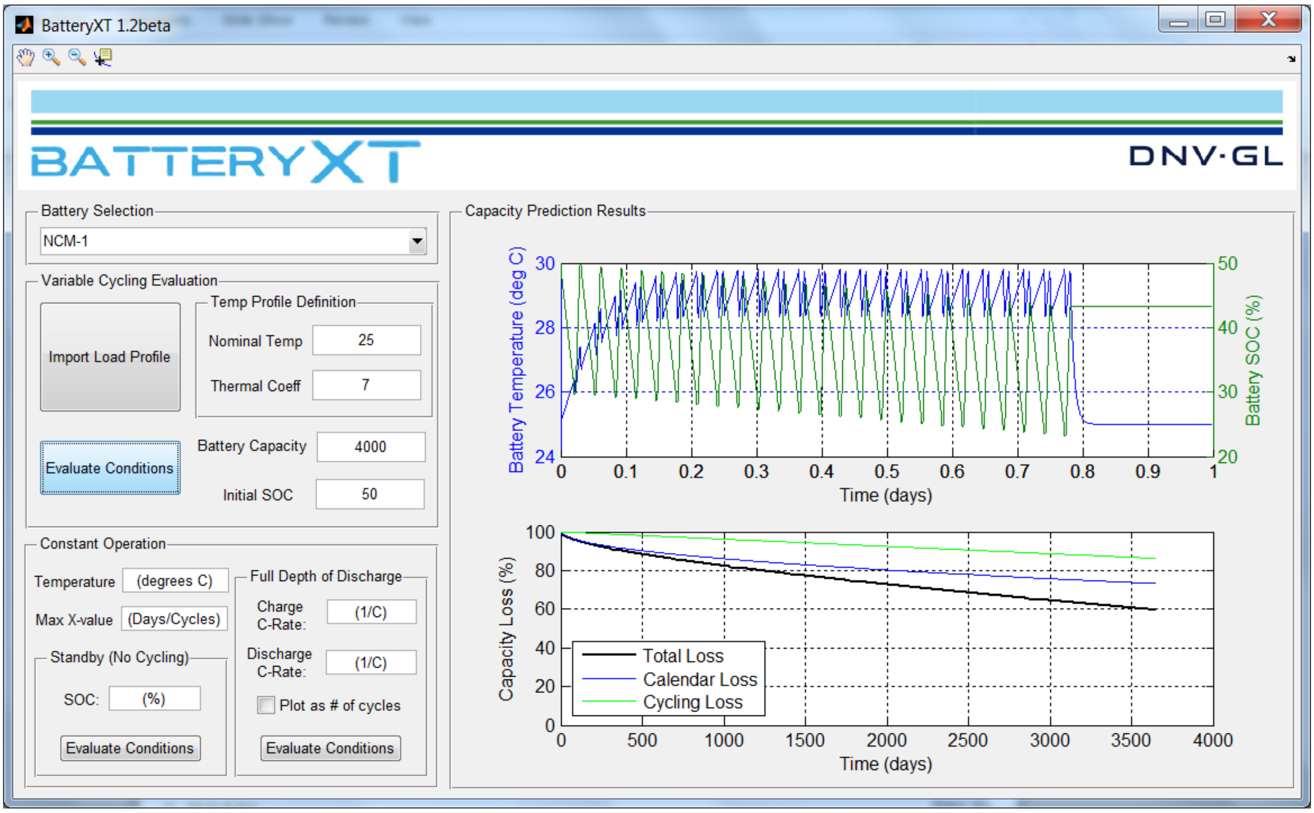

Figure D.2. Screenshot of Battery XT, showing user inputs which allow them to evaluate any chosen battery chemistry for any given application profile.

APPENDIX E. TECHNICAL FEASIBILITY AND ENVIRONMENTAL BENEFIT

DNV GL Battery Ready Service

DNV GL provides decision support to make vessels ready for future battery retrofitting or for battery operation. DNV GL can assist to select the best option according to operational and environmental requirements. There are two main options:

Ready for future battery retrofit

Build a vessel that will use a diesel or gas based power system that can easily be retrofitted with batteries in the future. This can be a good option for ships under construction or existing conventional designs.

Benefits

- DNV GL validates that the system is optimized for easy retrofit
- Minimum investment requirement
- Cost-benefit assessment pinpoints when a full conversion is attractive
- Increased confidence for owner, charterer, investor and other stakeholders

Ready for battery operation today

Build or retrofit a vessel with battery system and engines/motors installed and ready to run on battery from first day of operation.

Benefits

- Cost-benefit assessment illustrates the vessels performance to ship owners and charterers
- Cost reductions from optimization of engine/ motor size versus battery size
- Independent and credible battery service life assessment
- Avoid engine loads where Tier III-solutions, such as LNG and SCR, have non optimum emission performance
- Optional storage of energy from waste heat recovery, regenerative braking and renewables
- Enlarged negotiation power towards battery vendors.

The Battery Ready process consists of four defined steps:

Power and energy system decision support

Technical feasibility:

- Battery/hybrid system location, sizing and range based on operational requirements and profile
- Engine/motor system location and sizing based on the ship operational profile
- Outline of key requirements for a Battery Ready design

Financial analysis:

- High-level financial comparison of engine/motor options and battery options including both invest- ment cost and operational expenses
- Sensitivity analyses considering impact of fuel/battery price development
- High level evaluation of strengths and weaknesses (e.g. SWOT analyses) of alternative solutions with respect to technical issues, environmental aspects and economy

Concept review

- Development of novel ship designs and detailed technical feasibility studies tailored to the specific design and technical challenges
- Power system analysis

- Hazard identification (HAZID) review to identify hazards which could lead to high risks in operation
- Assistance with review of design and/or outline specification.

Approval in Principle

- Verification of the design concept and confirmation of compliance through DNV GL's Approval in Principle
- Support in the identification and mitigation of risks associated with a given design to ensure the development of a safe system right from the beginning

Risk assessment

- Risk assessment to identify, assess and manage safety and business risks
- Battery system safety risk analysis (mandatory for DNV GL Battery Power Class notation)

Environmental assessment

Battery production is energy intensive and therefore there has been several studies investigating the life cycle CO2 equivalent emissions of hybrid and battery cars. In Ellingsen et al.[11] a thorough analysis was done on the CO2-eq. emissions during the production of a 26.6 kWh NMC automotive lithium-ion battery installation, approximately the size of the battery installation for the Nissan Leaf. The study concluded that the emissions during battery production were between 172-487 kg CO2-eq./ kWh.

In a study for the Norwegian NOx fund[12] the environmental payback period compared to a traditional drive configuration was calculated for a hybrid PSV and an electric ferry.

For the hybrid PSV, the environmental payback period for GWP and NO_x is 1.5 months and 0.3 months respectively. For the fully electric ferry, the environmental payback period for GWP and NO_x and 1.4 months and 0.3 months, respectively, when the Norwegian electricity mix is used. For EU electricity mix, the GWP payback time increased to 2.5 months and for a global electricity mix the GWP payback time increased to just under one year.

[11] L. Ellingsen, "Life cycle assessment of a lithium-ion battery vehicle pack", Journal of Industrial Ecology, DOI:10.1111/jiec.12072.

[12] S. Laselle, L.O. Valøen, B. Gundersen»Life cycle analysis of batteries in martime sector» Prepared for Næringslivets NOx-fond by Maritime Battery Forum.