Project BLUE BATTERY, Part II:

Assessment of existing fire protection strategies and recommendation for future work

DBI FIRE AND SECURITY

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Content

Preface

This report was produced as a delivery from the project BLUE BATTERY which was completed in collaboration between *Danish Institute of Fire and security Technology* and *Danish Technological Institute*.

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The outcome of the project is two primary reports:

- Project BLUE BATTERY, Part I: Analysis of fire risk scenarios of existing and upcoming large maritime battery systems
- Project BLUE BATTERY, Part II: Assessment of existing fire protection strategies and recommendation for future work

1 Introduction

Maritime vessels are traditionally powered by fuel engines, but in the resent years, the idea of electrically powered vessels or a hybrid where both technologies works together has become increasingly popular as a result of international demands for lower pollution in general and lower CO_2 emissions in particular.

Lithium-ion cells, like in the car industry are the most likely candidate for this technology due to the high energy density, high power density, low self-discharge rate, long service life and decreasing prices of these cells. However, like combustible fuels, large battery pack systems may catch fire and in rare cases, even self-ignite. The causes for a battery fire, the fire development and the measures to prevent a battery fire are not similar to those of combustible fuels, and the methods to extinguish the fire are often different as well.

At this stage there is no set of fundamental guidelines to follow with regards to fire safety on-board vessels and the use of energy storage systems (ESS) (i.e. lithium-ion batteries). The current system, with regards to fire protection concerns in this emerging technological area works on a case-by-case basis; the explanation for this is due to the technology not being mature enough within the maritime sector to have very specific guidelines developed. The technology (ESS and batteries themselves) is also going through a steep development phase at this point in time, and the current technology may be obsolete within a short period, hence any form of strict, specific guideline may also be made obsolete before it is published or made public.

However, having some form of regulatory guideline would still be an advantage as currently each entity or company that has an invested interest in this area, seems to have developed their own form of strategy, guideline and/or hazard assessment with regards to 'safe' battery management, use and the associated fire safety concerns. Among these, are entities such as DNV, Lloyd's Register, the National Fire Protection Association (USA), etc.

In this document, current fire protection considerations are outlined along beside a review of the current state-of-the-art with regards to protection systems for batteries. After this, current fire suppression and extinction techniques are investigated for li-ion battery fires. A review has then been performed, investigating the current forms of guidance/recommendations and what they suggest in terms of fire protection, not much focus was given to the actual current regulatory schemes as this has been covered extensively in another report[1], which the reader is referred to for more details on this topic. Relevant standards are then listed with the purpose of acting as inspiration for the maritime sector as no current standards with regards to li-ion battery are currently in place with this area.

2 Fire protection considerations and State-of-the-art

In this section a detailed summary is provided with regards to fire protection methods for battery systems. The aim of this section is to provide the reader with more in-depth knowledge on current and future methods that may be useful in combating the fire hazards associated with battery systems. This section is provided as a complement to the summary of current guidelines provided in the following sections, in order to illustrate the background information that should be considered when any guidelines are written. It shall also summarise current state-of-the-art research on the topic of fire protection of batteries, to provide the reader with some knowledge on the future direction of the issues, and to provide some more detailed recommendations that may be considered in any future guidelines.

It is one of the more important general recommendations of this document that fire protection measures need to be taken at cell, module and pack level. On top of this the fire protection strategy must also consider additional hazards from within and without of the battery compartment itself. All of this inherently add complexity to the design of these systems, and increases the risk for errors to occur, which should be a consideration.

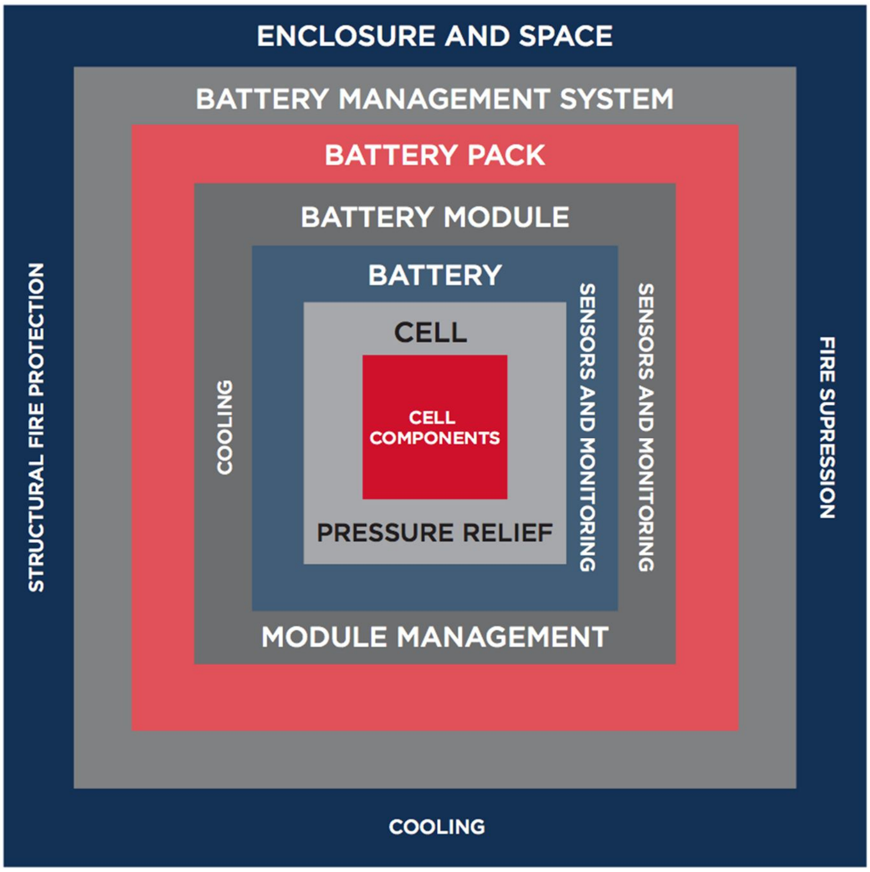

Figure 1 - levels of fire protection [2]

2.1 Fire protection at cell level

At cell level, safety measures can be taken inherently by design and by adding safety devices.

Thermal runaway starts with SEI (solid electrolyte interface) layer decomposition on the anode. The SEI layer can be modified by mild oxidation, deposition of metal oxides, coating with polymer or other materials in order to smooth the SEI surface and cover active edge structures. As a result, the direct contact between the active anode material and the electrolyte is prevented or reduced and higher temperature stability achieved. For more detail the reader is referred to Project BLUE BATTERY, Part I [15].

The cell is normally denoted by its cathode chemistry: Cobalt ($LiCoO_2$), Iron-Phosphate ($LiFePO_4$) and so on. The choice of cathode material influences the safety due to the fact that the temperature at which the decomposition of the cathode starts varies depending on the material. As an example decomposition starts around 130 ^oC for $LiCoO_2$, at 240 ^oC for NMC, at 270 ^oC for LMO and at 310 ^oC for a $LiFePO_4$ cathode. The cathode can be coated with a metal oxide or other materials to prevent direct contact with the electrolyte and thereby reduce site reactions at the cathode. New materials are continuously being developed and temperature-sensitive or voltage-sensitive electrodes with the ability to reduce or shut down the battery current at excessive temperature or voltage will eventually be introduced to these systems.

The electrolyte is often mentioned as the secret recipe by battery manufactures because of the mysterious additives, which provide the battery with its extraordinary performance. The electrolyte is a non-aqueous mixture of organic carbonates with a lithium salt such as LiPF6, $LiAsF_6$, $LICIO_4$ or $LiBF_4$ dissolved. Some additives as for instance Succinonitrile have been reported to reduce the amount of gas released at high temperature, to increase the onset temperature of exothermal reactions and decrease the amount of exothermal heat. Overcharge protective additives for the electrolyte are being investigated. Flame retardant additives based on organic phosphorus compounds have been reported to have some effect.

In various research [3][4][5][6] (given as examples) non-flammable or flame retarded electrolyte has been investigated as a means to reduce the risk of thermal runaway incidences. The concept here is to simply take away the source of fuel that flammable electrolytes provide. Thus, reducing the risk of battery fires. However, changing the electrolyte may reduce the general performance of the cell.

AUTHOR RECOMMENDATION: Use of non-flammable or flame retarded electrolytes could be given preference over other flammable electrolytes when application in commercial batteries is possible without compromising the performance.

Cylindrical and prismatic cells are normally fitted with a safety vent, which releases gasses when the internal pressure gets too high. The gas release prevents the cell case from cracking and exploding, but once the gas has escaped, atmospheric air will enter the cell and react with plated lithium (if any), so the cell may catch fire anyway. In addition the gasified electrolyte released is generally considered highly flammable.

AUTHOR RECOMMENDATIONS: At the battery cell level, safety mechanisms involve cell design features such as safety vents; shutdown additives, current cut-off devices and separator materials should be considered. As these are essential to prevent the occurrence and/or limit the extent of *consequences of internal malfunction at individual cell and battery pack level. The system must be designed in a way that any material vented is safely contained and directed to a safe venting space into the surroundings.*

According to [7] all toxic gas production seems to be dependent on the SOC (state of charge) of the battery, when SOC increases, the measured ppm of these gases also increases and production time is shortened. However the total production amount of these gases seemed less effected by the SOC, with the notable exception of SO_2 and HF. In this research the measured SO_2 concentrations were higher in a fully charged battery.

Hydrofluoric acid (HF) gas is highly toxic and can result from the combustion of battery cells containing fluorine [15].

AUTHOR RECOMMENDATION: Develop alternatives to the battery components that decomposes into fluorine when exposed to fire. This will mitigate the high-risk toxic gas.

Additional measures to consider:

Positive temperature coefficient device (PTC) – PTC devices work by responding to increased currents passing through an element. Heating up of the device occurs due to the Joule effect, which is translated into an increase on the resistivity of the device, which in turn would limit the current flow. Kise et al. (2007) described the use of internal PTC components for the positive electrode material of the cell based on carbon black/polyethylene mixtures coated on the positive electrode together with acetylene black. Internal PTC elements are considered safer than external PCT devices as external PTC devices cannot prevent the occurrence of internal short-circuit. Cells with a conventional $LiCoO_2$ positive electrode containing 12 % of the PTC were overcharged up to 10 V did not result in fire or explosion.

Redox shuttles for lithium-ion batteries – According to Chen et al. (2009), a redox shuttle is an electrolyte additive that can be reversibly oxidised/reduced at characteristic potential and provides an intrinsic overcharge protection for lithium-ion batteries that neither increases the complexity or weight of control circuit nor permanently disables the cell when activated.

Redox shuttles differ from inactivation agents/thermal runaway inhibitors. Inactivation agents are based on polymerisation of the additive or electrochemical reactions forming copious amounts of gas that triggers cell venting leading to irreversible inactivation of the individual battery cell and the whole battery pack. According to Chen et al. (2009) redox shuttles for good overcharge protection should be stable after hours of operation and a redox potential between 0.3 and 0.4 V above the operating potential of the positive electrode. However, the technology has to be developed and commercialised into efficient products that doesn't reduce the capacity of the cell.

In most cases, improved cell safety has a cost on other cell parameters such as price, capacity or power density. In the same way high quality may add to the price, but if the risk of spontaneous internal short circuits is reduced, it may be worth to pay. Raw materials may be contaminated with impurities and the production processes may add moisture and more impurities, so high skills and top professional production facilities are needed to produce high quality cells.

2.2 Safety at module and pack level

Large battery packs can be made in numerous ways, but regardless of the architecture at this level, adequate electronic control to prevent overcharge, over discharge and overheating of the battery packs is necessary. This is undertaken by the battery management system, which must always control the battery pack to assure that all battery cells are operated within their safe operation area, and a thermal management system must provide the cooling needed for any intended operation.

2.2.1 Battery Management system

The BMS (Battery Management System) is the main safety device in a large battery pack. In short, the main safety function of the BMS is to shut down the battery pack in case the voltage, the current or the temperature of any cell or module exceeds the specified range, and warn then the operator about the incident. Often the BMS will control the load and charger so that a shutdown is unnecessary. In addition, the BMS should be designed to operate the battery pack for optimum application performance and a long service life, which normally includes balancing.

Sensors measuring voltage and temperature on cells and modules provide inputs to the BMS. The current is measured in serial strings, whether formed by cells or modules. Voltage and current is measured at the battery pack terminals and additional temperature measurements from the terminals, the pack casing, outdoor and other places may be needed to control the thermal management (See next section). All these inputs are transferred to the central BMS, which is often a computer system. Depending on the BMS architecture some of the BMS functions may be performed locally in each module or other units, since the sensor connections to the BMS may count up to several hundreds or even thousands. Local BMS units can then communicate with the central BMS by a digital line rather than a large number of analogue connections.

Normally several outputs are available from the BMS. First of all the BMS must be able to reduce or cut out the load or the charge current by a circuit breaker in case of a critical malfunction. In a parallel connection of modules, it may only be necessary to cut out one module. As mentioned earlier such a malfunction could be a voltage, current or temperature out of specified range of cells or modules, but it may also be a malfunction in the thermal management system, the high voltage system, the communication system, the charger or elsewhere.

The BMS provides a number of outputs, which are indirectly connected to safety. State of charge (SOC) is a measure of the amount of capacity left in the battery pack and matches the fuel gauge in a car. SOC is calculated from the voltage and/or the amount of current drawn from the battery since last full charge (coulomb count). Several different algorithms are developed for the SOC calculation, which also depends on SOH. State of Health (SOH) is a measure of the battery pack aging. Whether in use or not lithium ion cells degrade over time, which means that the capacity is fading and the internal resistance is rising. The degradation rate is strongly affected by temperature, the usage pattern and the battery chemistry. Therefore 100 % SOC is a measure of another capacity after 10 years of use, than it was originally.

When the battery pack is manufactured, the manufacturer strives to use matched cells, which means that the cells have the same capacity when charged and discharged between the same fixed voltages. The aging of cells, however, yields some differences due to inherent cell differences and to differences in the usage pattern (E.g. temperature gradient in the battery pack). Therefore a single cell in a serial string may be empty even though other cells have more than 30 % of their capacity left, whereas another cell may be full even though the cell mentioned before could be charged with another 30 % of capacity, and therefore the battery pack seems to have only 40 % of its original capacity left. The solution is to balance the cells at the end of the charge. Several methods of balancing are available and normally the BMS is involved in the process. Balancing is normally performed at the end of the charging process. In a parallel connection of cells, balancing is unnecessary, since the potential over the cells are always the same, whereas the current through each cell will differ. If one of the cells in the parallel connection ages faster than the other cells or has a minor flaw, it will be forced beyond its voltage limits, and the phenomena is undetectable for the BMS. Although the parallel connection technic is less complex and less expensive, it opens the door to a risk that increases with the battery age.

AUTHOR RECOMMENDATION: Use serial connections at the cell level to take away risk of undetected phenomena that may occur if batteries are connected in parallel.

For safety and lifetime reasons, it is desirable that the BMS control the charging rather than having a fixed charging controlled by the charger. The BMS can then adjust the charging current according to the temperature, SOC, the energy needed and the time available for the charging. Charging control by the BMS requires communication between the charger and the BMS as known from car industry (EV & PHEV). During charging, the BMS will control the charger current including start, rest and stop times.

AUTHOR RECOMMENDATION: Let the BMS control the charging.

Although a high quality BMS may be able to handle most safety risks, faults in the sensors, circuit breakers, the BMS itself, or other devices may occur. Hence, an extensive self-diagnosis program including the whole BMS system is desirable to minimize safety risks in such a fault situation. In some cases, redundancy may be applied, like for instance redundant circuit breakers.

AUTHOR RECOMMENDATION: Extensive self-diagnosis program including the whole BMS system should be applied.

As mentioned earlier battery cells may develop a spontaneous internal short circuit. In some cases it should be possible to spot an internal short circuit or dendrite shorts at an early stage by letting the BMS monitor the self-discharge rates of each battery cell. Then the cell can be replaced before thermal runaway occurs. The efficiency of the method is still being discussed within the research field.

To display the battery status, the BMS should be connected to a monitor (PC, smart pad, smart phone). This connection could be used for maintenance as well. Any malfunction detected by the BMS should be reported as an alarm, where immediate response is required, or a warning, where only a receipt is required from the operator.

AUTHOR RECOMMENDATION: Information about faults should be logged as well as historical data about the battery pack and the use of it. The log can then be applied for maintenance, and it is useful in order to calculate SOC and SOH [20].

2.2.2 Thermal management

Along with the BMS, the thermal management system is the heart of the safety protection of large battery packs. The thermal management system is often controlled by the BMS, and it must remove heat energy when battery cells or modules gets too warm and add heat energy when battery cells or modules gets too cold for charging if necessary.

To secure the safety, prolong the battery lifetime and optimize the battery performance, the thermal management system should maintain optimum operating temperature for each cell in the battery pack, and reduce temperature variations within each battery module and among the modules. Heat may be generated by the battery pack itself or by ambient conditions.

The thermal management system can be designed for a moderate charge/discharge load at moderate temperatures, which means that the BMS must reduce the load if excessive cell or module temperatures are reached. Otherwise, the thermal management system must be designed for a very stressful load at high ambient temperatures. Abuse situations may be taken into account as well. Many cooling and heating technologies are available and some of those for cooling are mentioned below:

- Forced air is a low weight, low cost solution easily integrated in the battery pack and easy to maintain, but the efficiency is low and the cooling/heating is not distributed evenly over the cells and modules.
- Liquid cooling is a more expensive solution, which adds more weight and complexity and normally possessing a low lifetime. The cooling/heating is efficient and may be distributed evenly over cells and modules.
- Heat pipes show a high efficiency and a long life, but the systems are complex and expensive to implement. The cooling is moderately even distributed.
- Phase change materials (PCM) as for instance paraffin wax can store the excessive heat energy and return it to the battery cells when the temperature drops below the transition point. PCM has a high efficiency, a long life, an evenly distribution of cooling/heating and the technology is easy to implement. The solution is not expensive and it may be combined with one of the other solutions mentioned above, however it may add to the amount of combustible material close to the battery cells.

2.2.3 Other safety devices

Contactors to disconnect the battery from the load (engine) or the charger should be redundant and/or the open status should be checked by the BMS to assure they are actually open. Other high power contactors should be checked as well.

Fuses or temperature dependent devices may restrict excessive currents. Diodes may be applied in parallel connections to avoid self-discharge trough a shorted cell.

2.3 The battery compartment

Even though the battery pack should be well protected against any abuse, failures in the safety system, unintended abuse or a spontaneous internal short circuit in a cell may start a fire in the battery. Therefore the battery compartment should be designed to cope with a battery fire and prevent the spread of fire into other areas of the vessel.

According to a report from SP Technical Research Institute of Sweden, there is the potential of pressure increase within the battery compartment becoming a risk in the event of thermal runaway, therefore it is advisable that opening and/or ventilation may serve as pressure release valves, and that systems within the compartment (including ventilation) can withstand such pressure increases. In addition, the report also suggests that walls between the battery compartment and adjacent rooms could act as a pressure release if designed in such away.

Combustibles should not be kept in the battery compartment and the materials in the compartment like venting ducts, cooling ducts or hoses, battery chassis and doors to the compartment should withstand high temperatures. Finally a suitable fire suppression or extinguish system should be installed in the battery compartment; this is discussed in the next section.

3 Fire suppression and extinguishing

When a lithium-ion cell ruptures due to thermal runaway, flammable electrolyte is released into the surroundings along with decomposition products like CO and H_2, and so the fuel and oxygen components of the fire triangle are present. Whether flames are developed depends on factors like temperature, pressure, gas composition, convection and the presence of an ignition source. Hence, a lithium-ion cell fire is combustion of hydro-carbonate gasses and it can be extinguished like other gas fires.

Depending on the cell size and the amount of electrolyte in the cell, a fire is retained for a few minutes or less. Then the adjacent cells will suffer thermal runaway within a few minutes if the heat transfer from the first cell is not prevented. As mentioned previously, the heat transferred between a cell suffering thermal runaway and the adjacent cells is often ample to trigger a thermal runaway in the adjacent cells even without open fire. In a large battery pack it may therefore often be more important to cool the battery cells than to extinguish flames from a single cell. Hence, a fire fighting strategy should be based on fighting open fire as well as cooling the cell on fire and the adjacent cells.

There are several methods to fight a lithium-ion battery fire and several extinguish medias are available. However, the best practice and the optimum fire extinguish medium for these batteries is yet to be determined. As stated in the previous section, there is very little information regarding choice of fire extinguishing systems in any of the guidelines found, and the hazard assessments from the NFPA and SFPE both state this as an issue that needs further research.

If we assume the battery manufactures are the best qualified to recommend an optimum fire extinguish media for their battery technology, these recommendations are given in the MSDS (Material safety data sheet), and a list of randomly selected MSDS recommendations are shown in Table 1.

Table 1: List of fire extinguish medias as recommended in random selected MSDS.

Company	Country	Date	Battery	Chemistry	Water	CO_2	Foam	Chemical Powder	Dry powder	Nitrogen	Sand	Halon*	Whatever suitable
Yuka energy	China	2011	Pack	LCO	No	X	X		X		X		
Makita	USA	2013	Pack	NCO	X		X		X				
Enertech	Korea	2017	Pack	NMC	X				X		X		
Samsung	Korea	2011	Cell	NMC	X				X				
Samsung	Korea	2016	Cell	LMO	X	X	X	X	X	X			
Saft	France	2009	Pack	LCO	X	X		X				X	
Bipower	USA	2017	Pack	LCO	X	X		X					
LG Chem	Korea	2013	Cell	NMC									X
Motorola	USA	2017	Pack	LCO	X	X	X	X					
Ideal	USA	2010	Cell	LCO		X	X	X					
SDPT	China	2016		LCO	X	X							
Bren-Tronics	USA	2013	Pack	LCO	X	X	X	X					

Advance Energy	USA	2011		LCO									X
Leo Energy	Singa-pore	2014		NMC	X		X						
IDX	Japan	2016	Pack	LMO	X	X	X	X		X			
Panasonic	USA	2015		NMC	X	X	X	X					
Total					12	10	9	8	5	2	2	1	2

*Note that Halon products are prohibited in Europe due to their impact on the ozone layer.

As can be observed from the table above, there does not seem to be a consensus on which extinguishing media is preferable. Water is the most suggested.

In the DVN-GL report considerations for ESS fire safety [8], a number of different extinguishing systems were tested: Water, Pyrocool, F-500, FireIce and an aerosol agent. All acted to extinguish the tested battery fire initially, however in some cases the battery fire was re-kindled once the stream was removed due to excessive heat still stored within the battery. It was stated in this report that the ideal battery fire extinguisher would be both highly thermally conductive and highly electrically insulating.

Water is thermally conductive and if it is freshwater it has a quite low electrical conductance. Salt water, though, has a high electrical conductance. Extinguishing is achieved by the large cooling effect it produces when applied directly on the battery cells. Water systems come in a number of forms, those being; *standard sprinklers* that produce water droplets in high volume from nozzles at the roof. These are considered quite reliable and robust systems. *Drenchers*, that discharge higher volumes of water, and *water mist* systems aerosolise the water into extremely fine particles. According to research from SP Technical Research Institute of Sweden, mist/aerosol systems have the potential to trap some of the toxic gases produced from a battery fire. However, they may have reduced cooling power simply due to the lower thermal mass of the fine particles and they may be unable to reach the heat sources deeply set within the battery recesses. These systems and all others tested by DNV-GL were electrically conductive, as the other systems still relied upon water as the dispersion medium. Others methods, such as dry powder and sand are insufficient to cool the cells but act to suffocate the fire, however generally require manual application. CO_2 and Nitrogen have a similar effect by reduce the available oxygen for the fires to burn, but these systems are reliant on sealed enclosures to be highly effective.

Although an extinguish media that provides exceptional cooling effects, may be preferable, depending on the design of the battery packs it may become useless if the battery cells are enclosed by a tight chassis, so that the extinguish media cannot be applied directly on the cells. Foam uses the combined mechanisms of cooling, separating the flame/ignition source from the product surface, suppressing vapours and smothering.

Other extinguishing media such as radical stealing media (e.g halon, FirePro), works by inhibiting, on a molecular level, the chemical chain reactions present in combustion. Although Halon is no longer a viable option, there are new systems coming into the market (e.g. FirePro) that produce the same effective fire extinguishing without the unwanted consequences to the environment.

When choosing an extinguishing media it is very important that the designer is very specific on the intended purpose and expected mechanisms of the extinguishing system. All media have their pros and cons and they should all be investigated in the decision process when the fire strategy is defined.

4 Current safety guidelines and hazard assessments

In this section, current guidelines on battery systems within the maritime sector are summarised to give an overview of the current state of guidance on this topic. Due to the lack of regulation within the area, many of the companies that have an invested interest within this sector seem to have developed their own guidelines on the topic. However these are still only giving broad guidance on "what should be thought about" when designing a system, as there are no current maritime regulations or standards that directly apply to battery systems.

4.1 DNV-GL Guideline for large maritime battery systems

The DNV-GL guidelines [9] provide a fairly extensive list of recommendations regarding the application of ESS systems within the maritime sector. These include recommendations of the battery space itself, including ventilation systems, and fire protection recommendations for both fire within the battery space and from outside (i.e. from adjacent compartments).

On the battery space (which includes thermal management system, ventilation, fire protection and air temperature regulation), it is first recommended that a safety assessment is undertaken, that will include:

- *Identification of all potential hazards with a list of all relevant accident scenarios with potential causes and outcomes, including that Li-Ion battery fires have extinguishing challenges.*
- *Assessment of risks including evaluation of risk factors.*
- *Risk control options.*
- *Actions to be implemented.*

According to the DNV guidelines, one of the key issues is to quantify the formation of flammable gasses and how the gasses are likely to disperse. With regards to the ventilation systems it should be assumed that the gases are highly flammable.

Suggestions on how to quantify this are given, e.g. *for a single cell, the highest rate of gas emissions from that single cell should be considered. For systems with propagation, the highest rate of propagation at the highest rate of gas emissions from a single cell should be considered as the dimensioning case*. It should be noted here that the DNV-GL guideline does not seem to suggest a method for determining the rate of gas emission. It is also noted that potential interactions between cells, causing gas emission rates to increase are not considered in the 'dimensioning case'.

DNV-GL lists some considerations for developing a strategy for ventilation and fire protection when temperatures above warning levels are detected. The reason stated being that there is a risk that flammable off-gases will be generated from the battery electrolyte solvents if cell temperatures go above certain values even before fire is imminent. However DNV-GL state that a cell can continue to function despite off-gassing, thus, adequate ventilation in the enclosed spaces affected can contribute to management of this risk and reduce the risk of fire.

An example of a ventilation and fire protection strategy is provided within the guideline:

1. Reduce or cut battery load.
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.

However it is then stated that a case-by-case assessment might be required to assess the risk for propagation of an event from an individual cell to multiple cells, or module(s).

Some direct recommendations are outlined within the guideline:

For the battery space:

- *The battery system should be provided with adequate protection from heat, ignition sources, dust, oil pollution or other potential harmful environmental influence to the system and its components. If practical, a battery space should be a dedicated room.*
- *Ensure proper detection of gases that may be emitted from the battery system in the event of a serious fault conditioning, relief and ventilation to prevent the formation of explosive atmospheres. (*Refer to detection systems section*).*

For fire inside the battery space:

- *Electrical and thermal control through the BMS without option for manual override of safety functions.*
- *Cell thermal runaway shall be kept confined at lowest possible level.*
- *Fire within several sub-packs must be assumed to be out of control. Vessel evacuation cannot be excluded.*
- *Early detection and increased cooling power will help to keep any fire under control.*

For fire outside the battery space:

- *Any fire shall not lead to temperature above 70 °C within battery modules for more than 30 min.*
- *If the cell temperature has exceeded the battery manufacturer's maximum temperature, the battery system needs to be re-certified by the battery supplier before it can be put back into use.*
- *Fire classes applied on walls, doors etc. shall protect the battery system, e.g. by A-60 fire separation, which indicates the duration the doors and walls must be able to withstand a given type of fire.*
- *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.*

Detection systems

- *Gas releases are only rarely distributed in even concentrations. A safety margin is therefore recommended. Often a gas detection limit of 20 % of LEL is applied to ensure early warning and since local concentrations usually will exceed the average concentrations.*
- *If the gas detection limit is likely to be exceeded, further assessment on measures to dilute and extract the gas generated are required.*

Ventilation systems

- *The ventilation system shall be temperature resistant and not impose any ignition risk to the ventilation products.*

Suppression systems

- *As a general fire extinguishing medium, either water mist or (heavy) foam should be considered.*
- *Heavy foam might have advantages, such as:*

  1. *Longer lasting cooling effect since heavy foam might form a "wall" around and between battery sub-packs with a good cooling effect (depending on layout).*
  2. *Potential off-gas which is warmer than air can be ventilated from a high position in the battery space while foam can be injected from the top and spreading slowly downwards.*
  3. *Surrounding foam can bind potentially flammable solid or fluid off-gas products while gases can be ventilated out.*

Other/General

- *The maximum cell temperatures over lifetime shall be monitored. This gives an indication on whether the system can be used further or needs exchange after a critical fault involving high temperatures.*
- *The responsible operators for a battery system shall have sufficient training to be able to decide when and in which cases the fire extinguishing in the battery space shall be deactivated.*

The guideline provided by DNV-GL was the most extensive found, and provides much direction with regards to implementation of battery systems within the maritime sector. However, although extensive, there does seem to be a lack of reference to specific test standards and the like, by which many of the requirements that are outlined in the guideline could be proved. This suggests that DNV-GL will be the ones to decide when sufficient evidence has been provided, which seems to be a less efficient method, and also invites room for variation on what is acceptable, depending on person, country etc.

4.2 Lloyd's Register – Battery installations: Key hazards to consider and Lloyd's Register's approach to approval

In this document[10], the structure is similar to what is given in the DNV-GL document, although it is a more condensed version, thus specific details shall not be elucidated here. Some of the potential hazards that should be considered are briefly outlined, thermal runaway and self-ignition/combustion are mentioned briefly, it then goes on to say that obtaining/proving this information should be up to the battery manufacturer. It also discusses the importance of cell chemistry, and how that may affect the choice of fire suppression methods, however it does not give any guidance on this topic, rather it states that "*This highlights the importance of integration between the battery manufacturer, who is best placed to determine such requirements, and the ship designer responsible for fire suppression systems. Fire testing should be carried out to prove the suitability of the chosen method*".

For battery systems, Lloyd's Register (LR) appraisal process uses an integrated approach to the acceptance of battery installations. LR states that due to the extensive range of cell chemistries, they do not consider that the use of prescriptive rules is currently appropriate. This gives flexibility to allow manufacturers to adopt new cell chemistries as technology evolves. Instead, LR proposes to carry out an Approval in Principle for proposed battery management systems and adopt a risk-based approach to accepting specific designs.

This means that LR needs to be involved from the concept design phase in order to assure the safety of the battery installation is to their standards. Not only as part of the vessel's electrical system but as part of the whole ship as a system. The aim of this method is to identify potential safety issues from the outset, preventing the need for changes to be made further along the ship's lifecycle when they become disproportionately expensive. These statements clearly illustrates that industry are the parties responsible for providing/proving the safety of their own systems.

Unlike the DNV-GL guideline, the Lloyds document does actually reference some standards that are used by them as a way to check the battery safety, however these are taken from other industries and sectors as there are currently no maritime specific standards to aid.

Standards referenced by Lloyd's are:

- UN DOT 38.3 Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria
- BS EN 62281:2013. Safety of primary and secondary lithium cells and batteries during transport
- BS EN 62619 (DRAFT) Safety requirements for secondary lithium cells and batteries, for use in industrial applications
- IEC 62620. Secondary lithium cells and batteries, for use in industrial applications
- IEC 61508 Functional safety of E/E/PE safety-related systems

These and more relevant standards are discussed further in the next chapter of this report.

4.3 ABS Advisory on hybrid electric power systems

This document [2] is specifically tailored to considerations for hybrid electric systems, and discusses the potential options that could be implemented in this case for marine application. Lithium-ion batteries are outlined as one of these options. It first goes through the 'basics' of li-ion batteries, their operation and how they are built-up from individual cells into systems. What is different in this document, compared to others that were reviewed, is that it is very clearly outlined that to ensure the safety of such a system layers of protection need to be considered. Protection from the cell level right up to the battery room (enclosure or space) is clearly defined. In addition, compared to other guidelines, a clear schematic is provided to help illustrate all the safety systems that need to be considered which would clearly help the engineers/designers. However what is outlined again, similar to other guidelines is very general and no specifics on what choices for e.g. the fire suppression system are preferable.

The document then goes on to explain some of the advantages and challenges of implementing li-ion batteries. Some of the highlighted challenges include;

- Complicated monitoring and protection circuits,
- Aging,
- Temperature sensitivity,
- Transportation and;
- Thermal runaway.

Finally this document also reviews a previous fire incident on a hybrid ship (refer Deliverable 1 document from complete review of this incident), and provides some 'lessons learnt', which is a nice touch for engineers/designers reading this document, as it provides some real world learning.

4.4 SCRIPPS Institution of Oceanography – Shipboard Li Battery Safety Guidelines

This guideline [11] is a much more practical document, it goes through the responsibilities of the engineers and designers, when implementing a lithium-ion battery pack.

Compared to other guidelines, in this document there are much more detailed instruction on handling the hazards that may be associated with battery packs. This includes defining the responsibilities of each stakeholder, battery design, handling and storage, as well as emergency procedures; handling a hot cell, gas release and fire. Relevant parts of this document are summarised below.

The general responsibilities that are suggested for engineers/designers are outlined as follows:

- The first step suggested is to perform a hazard analysis to understand the various failure modes and hazards associated with the proposed configuration and type(s) and number of batteries used.
- Based on a hazard analysis, incorporate appropriate safety-related design and testing criteria into battery pack and device design, with the design objective of increasing the

safety margin during the battery pack life cycle. Ensure safety-related requirements are incorporated into design.

- Ensure that written standard operating procedures (SOPs) for Lithium and Lithium Ion powered devices are developed that include mechanisms to mitigate possible battery failures that can occur.

- Ensure that acceptance and quality-control procedures include verification of safety design features.

Responsibilities of the Vessel Safety Coordinator

- Implementation of the applicable provisions of SOPs and this Guideline, including emergency procedures.

- As appropriate, include lithium and lithium ion battery emergency response procedures in drills.

Apart from the responsibilities of stakeholders, this document outlines considerations for the design and implementation of battery systems. Although too extensive to include here, it does provide some additional hazard control measures that may be of relevance:

- In-line fuses should be fitted external to the battery such that they may be replaced after a short circuit is cleared.
- Thermal cut-off (TCO) or resettable polymeric, positive temperature coefficient (PTC) resistors can be used to limit cell temperature rise when that rise is caused by external current flow through the protective device.
- Both the surrounding thermal environment and the heat output of a battery pack and/or individual cells should be evaluated.
- For larger packs or for batteries running at high rates, additional thermal management must be considered. For example copper or aluminium heat sinks could be incorporated into the pack design to effectively conduct excessive heat away from the cells during discharge.
- Cells connected in series should not contain a centre voltage tap. This will eliminate the possibility of cells being unequally discharged.
- Batteries should not be tampered with, without first consulting the manufacturer.
- Battery pack construction should take into account the need for cell vents to function (where applicable). There should be an unrestricted escape path for the fumes such that pressure does not build up in the battery pack or housing. A vent mechanism should also be incorporated in rigid housings to avoid rupture or an explosion in the event of overpressure.
- Shock and vibration requirements must be considered in the design of any battery pack. All cells must be protected from excessive shock and vibration.

4.5 NFPA - Hazard Assessment of Lithium Ion Battery Energy Storage Systems

Although not specifically aimed towards the maritime industry, this report [12] proved to be a good resource on understanding some of the potential gaps in knowledge with regards to battery safety. Of particular interest within this report were the statements regarding concerns about the lack of information contained in local, state and national codes and regulations related to Li-ion ESS. This should be taken as a general comment within most industries, as lack of information is also a perceived problem within the maritime sector.

Some of the other highlighted concerns given in this report included;

- Volume of electrolyte in the Li-ion battery being used to define its hazard level (which is not appropriate for Li-ion battery chemistry).
- Selection of appropriate fire suppression and detection systems for an ESSs.
- Whether or not these batteries are considered hazardous materials.
- Separation of ESSs from other portions of the building.

These concerns highlight the fact that this is still an emerging market, with a lot of unknowns that require more research. Of particular interest to this report is the concern regarding fire suppression and detection, and separation of the ESS from other areas, these both are concerns that must also be addressed with regards to the maritime sector. Understanding how these products should be classified in terms of hazard, especially to the marine environment is also an important factor, but is out of the scope of this report.

Another important point from this report is that, of the current standards that are out there for battery safety, many were written for lead-acid battery installations, and thus may be misleading to use for lithium-type batteries.

4.6 SFPE – Lithium ion battery hazards

Similar to the NFPA document, although not specifically addressing the maritime industry, in this report [13], it was also written that at the current point in time, there are no specific fire protection standards that address lithium-ion battery cells. The authors also note that with regards to suppression systems, the publicly available information from testing conducted to date does not allow a comprehensive assessment of whether traditional water-based automatic sprinkler systems, water mist systems, or some other water-based suppression system would be most effective in the protection of stored Li-ion cells or batteries.

The authors also point out that a number of features specific to Li-ion batteries could make any of the existing battery classifications inaccurate and the recommended fire suppression strategy may not be appropriate, these include:

- Flammable versus aqueous electrolyte;
- The potential to eject electrodes/case material (projectiles) upon thermal runaway;

- Latency of thermal runaway reactions (cell venting can occur sequentially and after a significant delay resulting in re-ignition of materials);
- Large format battery packs may exhibit voltages much higher than typical batteries; and
- Individual cells generally have metal versus plastic outer shells [1]

[1] *Author remark: Prismatic cells usually have plastic enclosure. The pouch for pouch cells is an aluminum foil cover usually covered with plastic.*

5 Relevant Standards

The increasing deployment of energy storage systems, particularly battery packs based on lithium ion chemistry in different engineering sectors has led to a significant growth in the exploration of knowledge about the risks concerning fire safety of batteries. This has resulted in concentrated efforts, to make sure that the battery manufacturers follow self-evaluation or external experimental testing procedures before employing their products for end user applications. Also, considerable research and documentation is available about the definitions of corresponding standards that layout guidelines and compliance obligations to align the product requirements in some sectors such as automotive vehicles and standalone power requirement applications.

It is to be noted that similar work, which provides guidelines to technology providers for maritime sector is not available in the form of product standards. Most applicable standards are taken from other industries and are test specifications rather than design standards. Of course the battery design must comply with the requirements in the test standards, but standards or guidelines for the best practice of safe battery design would be useful. There are very few standards specifically for maritime applications, and therefore standards for vehicle and other battery systems may be consulted to identify common issues that may be relevant from the perceived risks associated with batteries employed on-board ships.

A comprehensive list of relevant standards is provided in Appendix 1, Relevant standards for reference.

As mentioned above specific standards for maritime application of batteries are lacking, in addition some further gaps have been identified as follows:

- BMS including battery status monitoring
- Best practice for safe battery design
- Mechanical and environmental tests for maritime battery packs (e.g. Bump & salt mist intrusion, corrosion – from salt water)

Based on findings from the review of the current guidelines and issues that were discussed in a workshop (Appendix 3, Stakeholder workshop), one frustration from the practitioners side is the lack of more clear guidance on how to implement battery systems in a new ship design. From the regulatory side, as discussed previously, the reason for the lack of more strict guidelines is the current pace of change and development within the industry, new chemistries and improvement to batteries make it hard. And the current mentality puts forward this idea that "every ship is different", and thus the full process required for any alternative design (HazID, risk analysis etc.) is still the preference.

One particularly interesting standard that was found within this was:

- UL 9540 A: Test method for evaluating thermal runaway fire propagation in battery energy storage systems.

This document, developed by Underwriter Laboratory (UL) provides a method of testing battery systems for fire hazards that does not depend on battery chemistry. It also provides methods by which battery systems should be tested at all levels, from cell up to the full system. This may be considered a potential 'step-in-the-right-direction' with regards to implementing some more clear guidance and steps on testing and quantifying how any new battery system may be tested with regards to fire concerns. The document is summarised in Appendix 2, Summary of UL9540A.

6 Qualitative study

As part of project BLUE BATTERY a qualitative study was performed. The purpose of the study was to investigate how the use of batteries as alternative energy source has impacted the daily practices onboard large passenger vessels and in what way it has influenced the perceptions of fire, risk and safety in the Danish maritime industry.

The ethnographic material from the interviews and field visits resulted in the insights listed below. For further detail the reader is recommend to read the full report [14].

- Overall, batteries are perceived to provide more safety, a more electric rather than mechanic maintenance and less strenuous work compared to diesel engines. In the light of changing weather conditions, geography, routes etc., batteries are perceived to increase the degree of operational reliability and flexibility in combination with diesel engines.

- Batteries are seen as an economically advantageous investment once installed and up and running because of the decreased need for fuel and the increasingly CO_2-neutral (and thus cheaper) form of operation and propulsion.

- According to the authorities, there have been major changes in the fire scenario plans and the safety procedures on board due to the introduction of batteries. However, the practitioners do not feel that much have changed due to the introduction of the batteries. According to the two crews, there have been no changes in terms of evacuation of the passengers and the only actual changes in fire safety have been limited to the technical area of the engineers.

- Technology and digitalization play a vital role in the risk and safety perceptions among practitioners and authorities. Technology is seen to provide an increased level of safety because it limits human interference and mistakes and ensures systematic safety barriers. The practitioners believe that batteries are safer than diesel engines and that thermal runaway is not a real risk but merely a theoretical one. Simultaneously, digitization and in particular hacking is seen as one of the top major threats at sea comparable with fire scenarios because the majority of alarms, detection systems, communication, and now also the battery propulsion systems are controlled digitally and/or via internet connections.

- Automated procedures now run, monitor and control either batteries or diesel engines, which means that the crew's work tasks have changed and their safety and working environment on board have increased. This also means that the responsibility of damage and the ability to define risk and safety is increasingly transferred to the manufacturer.

- There is an ongoing debate in the maritime industry about what the safety level must be concerning batteries as an alternative energy source. This debate has found no answer so far. The lack of specific regulations and guidelines apart from MSC.1/Circ. 1455, and the subsequently thorough, difficult and time consuming risk assessments based on IMO 1455 performed specifically for each new vessel with batteries on board frustrates the industry. It is discussed whether using "risk assessments" as a method instead of discussing a meaningful "safety level" provides more fruitful insights into potential hazards and accidents concerning the use of batteries in the propulsion system.

- The industry wishes more clear guidelines on the use of batteries and a minimum standard for the safety level. The authorities seek to solve this problem by encouraging the IMO to develop an international battery code.

7 Conclusion

What is clear from reviewing the current fire protection strategies and all the guidelines, hazard assessments and standards that are available, along with the conclusions from the qualitative study, [14] is that battery propulsion is a paradigm shift in terms of fire safety considerations. With regards to fire protection, it is obvious that fire hazards really need to be considered at every level from individual cell to the entire battery space, as well as being considered holistically as a part of the ships infrastructure. Even the crew mentality and competences requires a shift from 'the old way of working', which adds another, often overlooked dimension to these new systems as it is unlike current propulsion systems, where the fire protection predominately starts at the engine room level, and the majority of ships crew has previous experience (from themselves and other crew members) to help in any situation that may arise. All these added requirements inherently increase the complexity of any set of protection systems that are implemented, which in turn adds a lot more room for error in design and implementation. Hence, the implementation of more direct guidelines would significantly help reduce time, risk of errors and encourage more ship owner/designers to take on such a project.

Current guidelines provide advice on the issues that need to be considered, however they are not specific enough to be of maximal use by designers and engineers. One stated reason for these generalised guidelines is due to the current advances in battery technology. The use of battery technology is currently increasing extensively. However, the technology has not seen any big leaps in the last decade. Instead, the technological development of battery systems has proven to be a continuous process of small improvements. Therefore, standards and guidelines could be developed without immediately being outdated. In the current situation, where the range of generally accepted standards and guidelines exist, the class companies (and others responsible) must be involved during the entire development process, but tend to leave it up to the battery manufactures and ship designers to do all the work, in proving their systems in whatever way they can (this is also the position of the regulatory bodies, e.g. DMA). This makes the process very long, complicated and uncertain, with increasing variability that may significantly reduce the desire of ship owners/builders to take on such a project, which in turn stifles innovation within the sector. In addition, as there are no specific maritime standards that provide methods by which the safety of these battery systems can be checked against which means that every time a battery propulsion system is being considered in the design phase, the process (under the alternative design methodology within the maritime sector) must be restarted from scratch.

Looking forward, sectors like the automotive industry can shed some light on some of the issues that need to be considered, and how future standards may take inspiration from this area with regards to testing the inherent safety of these battery systems. Specifically with regards to securing batteries are protected against possible abuses. There is also the option to tests systems for the fire properties, making the variation of cell chemistry less important as you just have to do the designated fire tests to quantify your system, then use that data to undertake a standard risk analysis rather than having to go through the more complicated alternative design methodology currently implemented.

It is also clear that much more research need to be undertaken with regards to appropriate fire suppression for these systems, as this was a clear point of uncertainty within nearly all the documents that were reviewed for this report. Obtaining a better understanding of the mechanisms involved with thermal runaway, and other potential fire risks associated with battery should also be highlighted as future research areas of interest if this area is to become more popular in the future.

8 References

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Appendix 1, Relevant standards

Introduction

The increasing deployment of energy storage systems, particularly battery packs based on lithium ion chemistry in different engineering sectors has led to a significant growth in the exploration of knowledge about the risks concerning fire safety of batteries. This has resulted in concentrated efforts, to make sure that the battery manufacturers follow self-evaluation or external experimental testing procedures before employing their products for end user applications. Also, considerable research and documentation is available about the definitions of corresponding standards that layout guidelines and compliance obligations to align the product requirements in some sectors such as automotive vehicles and standalone power requirement applications. It is to be noted that similar work, which provides guidelines to technology providers for marine sector is not available in the form of product standards. Most standards are test specifications rather than design standards. Of course the battery design must comply with the requirements in the test standards, but standards or guidelines for the best practice of safe battery design would be useful.

There are very few standards specifically for marine applications, and therefore standards for vehicle and other batteries are consulted to identify common issues that may be relevant from the perceived risk associated with batteries employed on board ships. The following section lists relevant standards applicable to be considered for cells, battery packs, electricals and automotive sector.

Cell standards

IEC 62620:2014 "Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for use in industrial applications" includes marine application and is mostly for performance test. Often cell specifications are included in the battery pack standards.

Battery pack standards

- IEC 62620:2014 "Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for use in industrial applications" includes marine application and is mostly for performance test.
- IEC 61959:2004 "Secondary cells and batteries containing alkaline or other non-acid electrolytes - Mechanical tests for sealed portable secondary cells and batteries". General specification of a few mechanical tests.
- The series of IEC 62660 includes performance, reliability, abuse and safety testing of lithium-ion battery cells intended for electrical road vehicles. Many of the safety tests in part 3 are somewhat similar to the tests in IEC 62133.
    - IEC 62660-1:2010 "Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 1: Performance testing"
    - IEC 62660-2:2010 "Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 2: Reliability and abuse testing"
    - IEC 62660-3:2016 "Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 3: Safety requirements"

- IEC 62133-2:2017 "Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary lithium cells, and for batteries made from them, for use in portable applications - Part 2: Lithium systems". IEC 62133-2 contains tests and requirements for Safe operation under use and reasonable foreseeable misuse, and many tests are similar to those specified in UN38.3, which is mandatory for the safety of transporting lithium-ion cells and batteries.
- ISO 12405-1:2011 "Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 1: High-power applications". Performance, reliability and abuse tests of battery packs for high power applications such as hybrid electric vehicles (HEVs) and fuel cell vehicles (FCVs).
- ISO 12405-2:2012 "Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 2: High-energy applications". Performance, reliability and abuse tests of battery packs for high-energy applications such as battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV).
- ISO 12405-3:2014 "Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 3: Safety performance requirements". Abuse tests of mechanical, climatic and electrical nature plus simulated vehicle accident tests.
- ISO/DIS 12405-4 "Electrically propelled road vehicles --Test specification for lithium-ion traction battery packs and systems -- Part 4: Performance testing" (under development).
- UL 2580 "Batteries for Use in Electric Vehicles". Contains safety requirements for energy storage assemblies (battery pack) used in electrical powered vehicles including electrical, mechanical and environmental tests.
- UL 9540 "Standard for Energy Storage Systems and Equipment". Standard for stationary energy storage systems and equipment (like charger, controls, power conversion and more). Comprehensive standard which deals with most parts of a large battery system.
- UL 9540A "Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems". Test and evaluation at cell, module, unit and installation level.

Electrical standards

- IEC 60092-305:1980 "Electrical installations in ships - Part 305: Equipment - Accumulator (storage) batteries"
- IEC 60092-501:2013 "Electrical installations in ships - Part 501: Special features - Electric propulsion plant"
- IEC 60092-507:2014 "Electrical installations in ships - Part 507: Small vessels"
- ISO 16315:2016 "Small craft -- Electric propulsion system". For small crafts up till 24 m.

Automotive battery standards and recommended practices

In this section, some of the major automotive standards are discussed in some detail as compared to the section above. This could provide some guidelines, which may be used as a yardstick to formulate new rules, recommendations to frame corresponding battery safety standards for the shipping sector which are faced with similar challenges i.e. fire safety issues concerning batteries installed onboard ships. The list is not comprehensive but provides an overview of the issues covered in such standards.

- Functional guideline for the electric drive battery pack system has been summarized under document J2289-200807 [1], by Society of Automation Engineers (SAE). It mainly describes the common practices for design of battery systems that utilize a rechargeable battery to recover all or some of the traction energy. This document includes product description, physical requirements, electrical requirements, packaging requirements, environmental requirements, safety requirements, storage and shipment characteristics, and labeling requirements. It also covers termination, retention, venting system, thermal management, and other features. Also described are the normal and abnormal conditions that may be encountered in operation of a battery pack system.
- Another standard which describes a test procedure for battery flame retardant venting systems is described in [2]. This SAE standard details procedures for testing lead-acid SLI (starting, lighting, and ignition), Heavy-Duty, EV (electric vehicle) and RV (recreational vehicle) batteries to determine the effectiveness of the battery venting system to retard the propagation of an externally ignited flame of battery gas into the interior of the battery where an explosive mixture can be present. This could be a standard which may be used for application for marine sector too.
- Another safety standard for electric and hybrid vehicle propulsion battery systems utilizing lithium based rechargeable cells is J2929[3], which defines a minimum set of acceptable safety criteria for a lithium-based rechargeable battery system to be considered for use in a vehicle propulsion application as an energy storage system connected to a high voltage power train. For shipping sector, if battery packs are to be used for providing auxiliary power to the engines for starting or other heavy duty operations, the points illustrated in such standard may still be useful to consider, since such battery packs are placed in engine rooms where temperatures are significantly high, which increases the risk of thermal runaway of batteries. Hence, the standard requirements for cooling of energy storage system, battery management system and other electronics may be used for marine batteries as well.
- Another recommended practice followed by manufacturers is to label the battery which is outlined in document J2936_2012 [4] by the SAE. This standard provides labelling guidelines at all levels of component, subsystem and system level architectures describing content, placement and durability requirements of specific unit throughout the total product life cycle from inception to reclamation. The main rationale behind this practice has arisen due to introduction of new technologies, applications and manufacturing techniques as well as new suppliers and governmental entities that have resulted in the need to address and standardise the labelling requirements of the component including handling and transportation information. So, perhaps if any fire extinguishing equipment has to be installed on board ships, such labelling requirements may prove to be handy for employing correct extinguishing methods for batteries on board ships.

- Another recommended Practice (RP) for shipping transport and handling of battery system is detailed in document J2950_201202[5]. It could happen that large consignment of batteries are transported as cargo on ships, then such a standard guidelines may be useful for employing safety measures for batteries on board ships. This recommended practice aids in the identification, handling, and shipping of new and used un-installed lithium ion battery systems to and from specified locations. The specific intent of this recommended practice is to identify, utilize and reference existing US and international hazardous materials (dangerous goods) transportation regulations, which are the only methodologies to be used to establish transportability of new battery systems. It is also the intent of this recommended practice to provide recommendations regarding diagnostic testing to be used by service and shipping personnel for the purpose of determining a used battery system's transportability. In support of the service and shipping personnel, the diagnostics process seeks to use standard tools of the trade and avoid laboratory type equipment. The main rationale behind this standard is that the transport of current and advanced technology battery systems requires knowledge of current transportation regulations as well as battery systems capabilities in assisting with self-diagnostics to help ensure battery system transportability.

Other Automotive Standards

- J1766 – Recommended Practice for EV & Hybrid Vehicle Battery Systems Crash Integrity Testing –defines test methods and performance criteria which evaluate battery spillage, retention and electrical isolation during specified crash tests
- J1772 - EV & Plug in Hybrid EV Conductive Charge Coupler defines the general physical, electrical, functional, safety and performance requirements to facilitate conductive charging of EV/PHEV vehicles.
- J2344 – Technical Guidelines for Electric Vehicle Safety – defines safety guideline information that should be considered when designing electric vehicles for use on public roadways.
- J2380 - Vibration Testing of Electric Vehicle Batteries describes the vibration durability testing of an electric vehicle battery module or pack
- J2464 - EV & Hybrid Vehicle Rechargeable Energy Storage System Safety and Abuse Testing Standard defines abuse and extreme environmental battery tests
- J2910 – Design and Test of Hybrid Electric Trucks and Buses for Electrical Safety - provides direction to manufacturers on design requirements and test procedures intended to make these vehicles safer to operate, service, or recover from an accident.
- J2929 – EV & Hybrid Vehicle Propulsion Battery Systems Safety Standard defines acceptable safety criteria for lithium based rechargeable battery systems.
- J2950 – Recommended Practice for Battery Transportation and Handling – defines guidelines for identification, handling and shipping of RESS
- J1797, AUG 2016, "Recommended Practice for Packaging of Electric Vehicle Battery Modules"

Gaps

The following gaps where identified for battery standards for marine applications:

- Specific marine applications
- BMS including battery status monitoring
- Best practice for safe battery design
- Mechanical and environmental tests for marine battery pack (Bump & saltmist)

Summary

A number of safety standards relating to issues concerning batteries are available via society of automation engineers (SAE), private fire test laboratories, and work done by various ISO committees. Such standards are drafted with the main target of ensuring smooth functioning of batteries on electrical vehicles or standalone power applications. In addition to fire safety, such standards address a number of other issues regarding battery performance in abusive conditions, mechanical, physical and chemical durability, charging requirements etc. Such documents can provide a starting point to gather relevant information about risks with batteries on ships as compared to those on cars and plug-in hybrid vehicles and standalone power applications.

Lesser information is available for standards concerning marine battery applications. Once clear articulation of such risks for marine applications is identified, the standard practices from automotive standards may be employed to draft new guidelines and regulations for marine sector.

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Appendix 2, Summary of UL9540A

The main purpose of the UL-9540A document is to provide details about the test method for evaluating fire characteristics of a battery energy storage system (BESS) that undergoes thermal runaway. The data generated is used to determine the fire and explosion protection required for an installation in case of such an event. The first edition of the document was published on 2nd November 2017 as a copyright property of Underwriters Laboratories Inc.

The following section provides a brief summary of the main contents. For details it is recommended to refer the original document:

> Underwriters Laboratories Inc. *UL 9540A - Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems*. (2017)

The document presents a methodology of testing applicable to battery energy storage system (BESS) at different hierarchical levels namely cells, modules, unit and installation level set ups to gain overview of the fire issue on different scales.

The outcomes of the test at each level are monitored with regard to different fire performance parameters such as heat release rate (HRR), gas generation and venting, gas compositions, surface temperatures, deflagration and monitoring any flying debris, measurement of surface heat fluxes and documentation of any explosions if observed.

The other set of monitored parameters are battery performance parameters (such as relationship between voltage and state of charge) at each level.

The document highlights the procedures that should be followed at each level of the abuse test i.e. at the cell, module, unit and installation level. The conclusion of the test provides a guideline for preparing a technical report with several details depending upon the observations found during the test and the level of complexity involved in it. For example the observations reported during the cell level test would involve information such as:

- Cell manufacturer name and cell model number
- Cell critical construction details
- Energy storage technology
- Energy storage capacity in Ampere hours
- Open circuit voltage and its variation with state of charge (SOC)
- Thermal abuse test observation and experimental data
  - Methods used to initiate thermal runaway
  - Temperatures (at which gases are first vented, maximum temperature prior to thermal runaway)
  - Flammable gas generation and composition measurements
  - Lower flammability of the cell vent gas

The main purpose of the *cell level* testing is to apply fault conditions on cells to force them into thermal runaway. In case no observations of thermal runaway are observed it is also suggested that it should not be necessary to conduct additional module or unit testing on BESS that utilize the cells.

On *module level*, the purpose of the test is to monitor the progress of fire within the module upon exposing them to fault conditions and forcing them into thermal runaway. The test establishes a base line fire test performance that can be evaluated against the fire performance of other battery modules the BESS manufacturer may choose to use within the system. While on module level further details with regard to testing are described, with the main focus behind the heat release rate calculation based on oxygen consumption calorimetry. The report generated as a result of the test includes experimental observations as reported on cell level in addition to heat release rate versus time data, maximum temperature, vent gas composition, documentation of the module enclosure integrity after the test, extent and duration of the flame propagation outside of the module, observation of flying debris during the test etc.

The *unit level* testing corresponds to evaluation of the large scale fire and fault condition performance anticipated by fire codes and energy storage system codes. The unit level testing details involve specifications for BESS unit in which an internal fire condition is initiated and target BESS units representative of adjacent systems in an installation. The testing specifications provide guidelines to place instrumentation for heat flux and temperature measurements and positioning specification of measured variables (HRR, Heat fluxes, Temperatures), spacing requirements between the units. The test report provides all the information cited above and in addition a number of parameters at the unit level testing such as observations to the damaged walls of the target and initiating BESS unit, flying debris, distances separating the units, module voltages, heat fluxes and surface temperatures, flaming outside the initiating BESS enclosures. Additionally, performance requirements are also listed regarding the units, which mainly define performance with regard to observations of flaming, surface temperature measurements along wall surfaces, modules and observation of any explosion hazards. The results are intended to be used to verify that fire within a single unit will not spread to other units nor breach the wall of the room or the BESS enclosure.

In addition to cell-module-unit level testing, additional tests are specified for performance requirements for effectiveness of sprinklers. Overall, the document provides the purpose of the tests, how individual tests relate to each other and interpretations of the test results to achieve a code compliant battery system installation. It also provides some guidance on choosing appropriate tests for large scale battery installations with regard to different configurations in which it could be tested such as spacing requirements for unit level testing, maximum BESS energy considerations, usage of integral fire suppression system, combustibles under the unit to mention some of them.

Appendix 3, Stakeholder workshop

In order to get feedback for the project a workshop with invited stakeholders was arranged at DBI November 23 2017.

The purpose was to present the project and preliminary findings to key representatives within the maritime industry and get their reflections based on practical experience and knowledge of the maritime framework conditions. The feedback was used to identify if the project was on the right track or if adjustments were needed.

Attendees represented a number of relevant companies within the industry:

- Lloyd's Register
- Scandlines Denmark A/S
- PBES – Plan B Energy Storage
- Danish Shipping (Danske Rederier)
- Danish Maritime (Danske Maritime)