



SAFETY AND TRANSPORT

Safe introduction of battery propulsion at sea

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Abstract

Electric propulsion using batteries as energy storage has the potential to significantly reduce emissions from shipping and thus the environmental impact. The battery type that is currently on the top of the agenda to be used for ship propulsion applications is Li-ion batteries. Li-ion batteries pose different safety issues than e.g. other propulsion technologies and other batteries such as lead-acid batteries. It is essential that the safety level on board, including fire safety, is maintained, when introducing electric propulsion with energy storage in batteries. This report discusses the different regulations and guidelines available today for fire safety of batteries on board in relation to current knowledge about Li-ion batteries. Also fire safety measures available on board ships today and their applicability for Li-ion batteries is discussed, as well as the different test methods available and their applicability. A workshop gathering different stakeholders from Sweden, Norway and Finland identified fire safety as the main challenge for the introduction of battery propulsion at sea. The workshop concluded that future work is desired in order to increase knowledge and to develop publicly available strategies, training and designs.

Key words: lithium-ion battery, sea, propulsion, fire, safety, detection, extinguishment

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Preface

This work has been financed by Västra Götalandsregionen together with RISE which is gratefully acknowledged.

Input for the report has been provided by several people representing different stakeholders. The input has been provided such as sending documents, feedback on the content of the report during its development and participation at a workshop held in Gothenburg

Sammanfattning

Batteridrift och användande av batteri för reservkraft är viktiga faktorer för att minska emissionerna från sjöfarten, framförallt när fartygen går inomskärs men även för internationell fart. I Sverige finns det idag ett fåtal fartyg med batteridrift medan man i andra länder t.ex. i Norge har fler. Det finns ett stort intresse att införa batteridrift hos redare i Sverige och Västra Götalandsregionen. Vid en workshop som arrangerades inom ramen för projektet blev det tydligt att mer kunskap om risker och fördelar med olika typer av batterier efterfrågas av sjöfartsnäringsen. Säkerhetsfrågor identifierades som det generellt största problemet att lösa för att introducera batteridrift.

De batterier som ligger närmast till hands att använda för elektrisk framdrift är Li-jon batterier. Li-jon batterier har många fördelar såsom högre energitäthet men även nackdelar vad gäller säkerhet. Det är viktigt att säkerhetsnivån bibehålls när batteridrift introduceras.

Denna rapport beskriver den kunskap som finns idag om Li-jon batterier och de regelverk och riktlinjer (guidelines) som finns för batteridrift till sjöss. Vidare diskuteras testmetoder och den brandsäkerhetsutrustning som finns normalt till sjöss och dess applicerbarhet på batterier.

En genomgång av regelverk och riktlinjer visar att det finns begränsat med råd för hur man designar batterisystem och skydd säkert. Man får förlita sig på information från tillverkare och klassningssällskap. Det saknas även provningsmetoder för att t.ex. utvärdera släcksystem för batterirum eller batterisystem på fartyg.

1 Introduction

Electric propulsion using batteries as energy storage has the potential to significantly reduce emissions from shipping, particularly for ships in coastal traffic like commuting ferries in the archipelago, but also for international traffic. Reducing the emissions is of great importance in order to meet environmental requirements.

Batteries have been used for a long time at sea for e.g. emergency power and radio installations but it is only recently that batteries have been introduced for propulsion. Such an application requires much larger battery installations than previously used. In addition are new types of batteries introduced such as lithium-ion batteries which are the most common new battery technology type for electric propulsion at sea.

Li-ion batteries pose different safety issues than e.g. lead-acid batteries and it is essential that the safety level on board, including fire safety, is maintained. This report discusses the different regulations and guidelines available today for fire safety of batteries on board in relation to current knowledge about Li-ion batteries. Also fire safety measures available on board ships today and their applicability for Li-ion batteries is discussed, as well as the different test methods available and their applicability.

When regulations and guidelines are discussed the terminology used in these documents is used which often means that the term “Lithium batteries” is used. However by Lithium batteries it is probably meant Li-ion batteries.

2 Battery technologies

There are two main categories of batteries; primary batteries which are non-rechargeable and secondary batteries which are rechargeable. Common non-rechargeable battery types are alkaline, zinc-air (Zn-Air) and lithium-metal (Li-metal), non-rechargeable batteries cannot be recharged and has to be thrown away when the energy has been consumed. Common rechargeable battery types are lead-acid, nickel-cadmium (NiCd), nickel-metal hydride (NiMH) and lithium-ion (Li-ion). This report focuses on rechargeable batteries. Primary batteries might be useful for specific battery emergency backup application, however secondary batteries are needed for battery propulsion at sea because the energy storage system needs to be recharged in or to use it for more than one trip.

Lead-acid batteries have been used for more than 150 years and are still produced in large quantities. Several types are available, e.g. free ventilated or recombination battery of types absorbent glass mat (AGM) and Gel. The lead-acid technology is fully mature and therefore cost-optimized but has lower power and energy densities and a significantly shorter cycle lifetime than nickel-metal hydride and Li-ion batteries. Lead-acid batteries also require a long charging time, typically 10 hours for fully charge. The safety concerns are typically related to acid and corrosive electrolyte and to the risk of hydrogen gas production during operation. Hydrogen gas can potentially ignite and explode but the buoyancy of hydrogen gas makes it relatively easy to ventilate the battery in order to avoid the formation of an ignitable mixture with air. Since lead-acid batteries are a mature technology, battery design is very well developed to avoid these problems.

Nickel-cadmium batteries offer significantly improved cycle life time and energy density compared to lead-acid batteries. NiCd batteries are still manufactured, however the market has dropped significantly due to its successor, the NiMH battery, and also the later Li-ion battery.

Nickel-metal-hydride batteries offer significantly improved energy and power densities compared to lead-acid and NiCd batteries. NiMH offers a high cycle life time and the safety concerns are relative small. NiMH do not, however, have the same energy storage capacity as Li-ion batteries. NiMH cells are completely sealed, however typically have a cell safety vent.

Lithium-ion batteries offers high energy and power densities, combined with a long life time and high efficiency. Their use is increasing, and Li-ion has recently also been introduced for electric propulsion at sea. The safety concerns are however larger for Li-ion batteries than for NiMH and lead-acid batteries due to the chemistries used for Li-ion cells. Li-ion cells are completely sealed and do not emit gases during normal use. However, cylindrical and hard prismatic cells typically have a non-reversible safety vent in order to release (vent) gases before extreme cell pressures build-up. Pouch prismatic cells vent when the cell pressure increases, but it does not need a safety vent since the pouch cell will break at moderate pressure build-up.

Often the term “Lithium batteries” is used both for the rechargeable Li-ion and for the primary lithium-metal batteries. It is however important to note that primary Li-metal and secondary Li-ion is not identical and use different principles, materials and have different properties. Li-ion batteries use Li^+ -ions while the primary lithium-metal batteries use lithium in the form of Li-metal. From a safety perspective they need to be treated differently.

The Li-ion battery cells have a positive pole (cathode) and a negative pole (anode) with separator in between. The separator is typically a polymer of polyethylene (PE) or polypropylene (PP) and have low electrical conductivity but have small holes to allow Li^+ -ion transportation. In order to have ion conductivity between the electrodes an electrolyte is needed. The separator is typically soaked with the electrolyte. Figure 1 shows a schematic illustration of the basic Li-ion cell build-up.

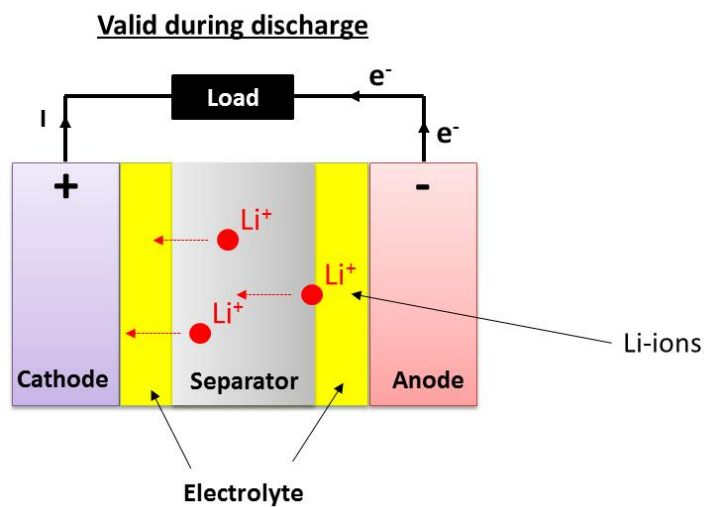


Figure 1. Schematic illustration of a Li-ion cell. During discharge, the electrical current goes from plus to minus while the electrons go from minus to plus. During charging the directions are reversed.

Li-ion battery cells have different packaging; cylindrical, hard prismatic or pouch (polymer, coffee bags) prismatic cells as illustrated in Figure 2. In a pouch cell, the layers are typically stacked on each other while for the cylindrical and hard prismatic cells the layers are wound, in a so called a jelly roll.

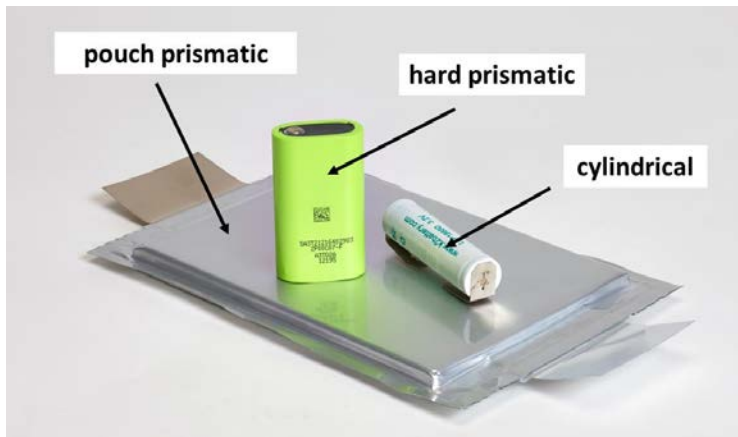


Figure 2. Photos of commercial cell examples with different packaging types; pouch prismatic, hard prismatic and cylindrical.

Li-ion is a family of battery cell types of different materials with the common feature that they use Li-ions. Therefore, the materials for the anode and the cathode can vary as well as the materials used in the electrolyte and separator. Theoretically there are a huge number of possible materials but only a limited number of these combinations are used in research laboratories, and just a few are commercially available. For the anode, today, essentially the most common is carbon/graphite and less common is titanium (titanite). For cathode, there are a few more, for example cobalt, nickel, manganese or mixtures of them (e.g. NMC, NCA) or phosphates. The most common of the phosphate cathode types is today lithium iron phosphate (LFP).

The exact electrolyte composition is more or less always different between each cell type/manufacturer. The electrolyte contains organic solvents, a lithium salt and a number of additives to improve stability, safety, life time, performance, etc. Due to the high cell voltage of Li-ion, about 4 V, water electrolytes cannot be used.

2.1 Battery systems

The battery system consist of several parts; e.g. battery cells, mechanical structure and protective box(es), thermal management system, electric connections and the control and management system, typically called the Battery Management System (BMS). The basis of a battery system is the battery cell. A multiple of cells are typically placed in a battery module and a multiple of modules are connected to form a battery pack. A multiple of modules can also be connected to form a subpack and multiple of subpacks can form a pack. Large battery systems can consist of a multiple of battery packs. Figure 3 shows a schematically illustration of general Li-ion battery system. There is no unified definition of a BMS, for example, in Figure 3, the fuse and contactors are separated from the BMS box, but they could also be inside the BMS-box.

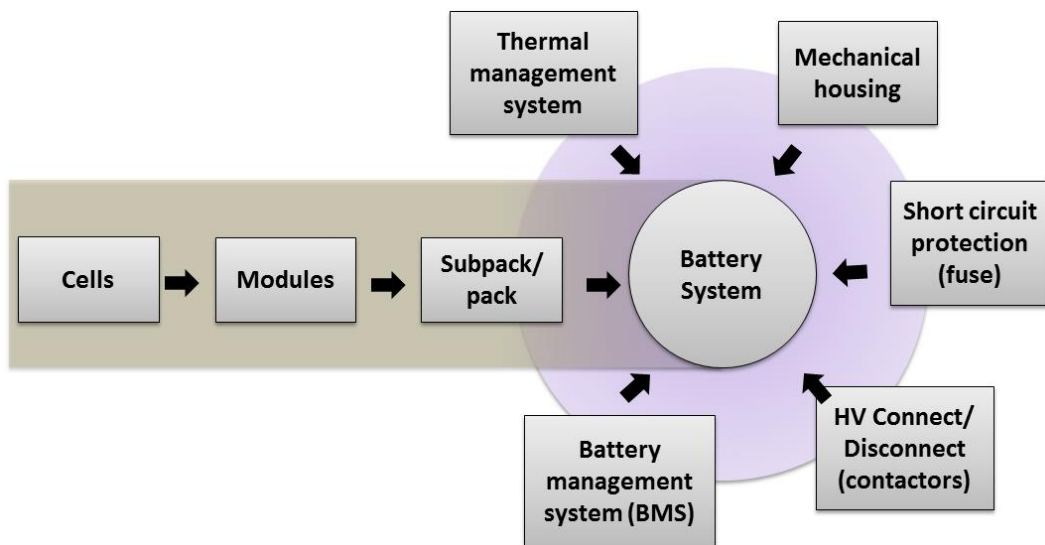


Figure 3. Schematic illustration of a general Li-ion battery system.

3 Battery use at sea

Batteries have been used on board ships for many years for storage of small amounts of energy, mostly in order to get redundancy in case of an emergency or a failure of the normal electrical supply. Since the cost of batteries has decreased and the amount of energy that could be stored has increased significantly during recent years it has become possible to use stored electric energy for ship propulsion in order to have lower environmental impact. Examples of different ships of different sizes utilizing propulsion from energy stored in batteries are given in Table 1.

Table 1 Examples of ships utilizing propulsion from energy stored in batteries.

Ship	Type	Length (m)	Passengers	Battery energy capacity (kWh)
Movitz	Passenger National Sweden	23	98	180
Ampere	Ropax National Norway	80	350	1000
BB Green	Passenger National Demo	20	70	400
Prinsesse Benedikte	Ropax International Denmark	143		2700
Fannefjord	Ropax National Norway	123	390	410
Opal	Passenger Expedition Iceland	33	60	240 - 360

The stored electric energy can be used in different ways. The electric engine could either be the main engine or it could be used together with a combustion engine. It could be installed in parallel or in serial with the main engine.

Ships with diesel electric propulsion systems are very well suited to be driven by electricity from batteries. The energy could be taken from the batteries only when e.g. travelling in sensitive areas where the diesel-generators produces undesired noise or pollution. Another approach used by m/s Prinsesse Benedikte is to let the diesel engines for the electrical production run on constant revolutions in order to let them work as energy efficient as possible and use the batteries for extra power when needed.

The most suitable configuration also depends on the routes and type of trade the vessel is engaged in. It could be anything from a small passenger ship used for river crossings or a recreational vessel used in remote areas, to a large ro-ro-passenger ship. This means that the battery installations will vary considerably in size between different ships. The larger installations could contain several MWh of stored electric energy.

4 Fire hazards associated with Li-ion batteries

The battery type that is currently on the top of the agenda to be used for ship propulsion applications is Li-ion batteries. They have many advantages when it comes to energy and power density but have drawbacks related to safety as they are only stable within a limited regime of operating conditions (e.g. temperature and voltage window ranges). Conditions that can bring the battery into a self-heating stage that can develop into a so called thermal runaway [1,2] includes overcharge, overdischarge, mechanical abuse, heating and short circuits as described in Figure 4. There is also a possibility that there are impurities in the battery cells originating from the manufacturing process or built-ups of dendrites that can cause internal short circuiting which leads to a thermal runaway.

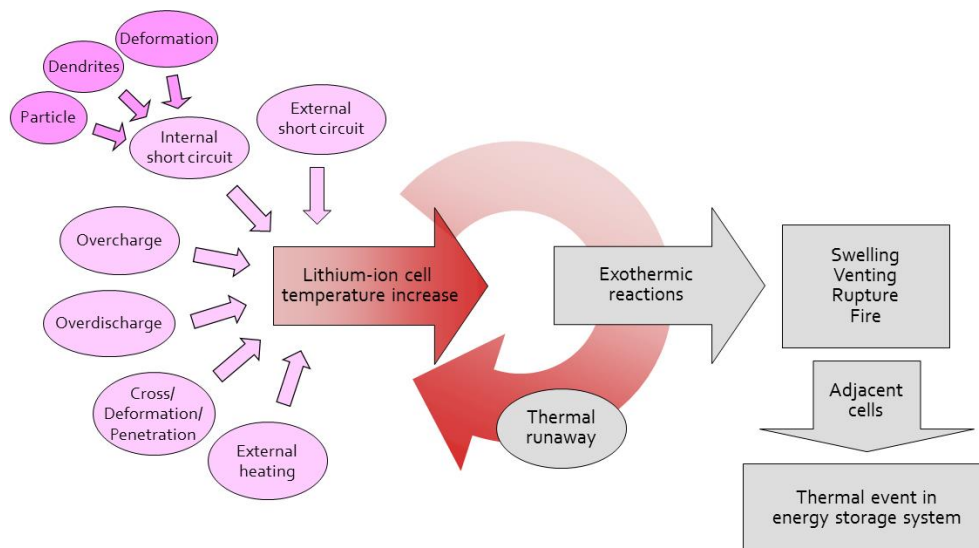


Figure 4. Potential chain of events leading to a thermal event on the cell level developing to system level.

What makes the fire hazard with Li-ion batteries different compared to many other fire hazards are that all prerequisites needed for a fire is available in the batteries; the fuel, the heat and/or spark and to some extent the oxygen. The oxygen is typically released from cell internal reactions involving the electrode materials.

A Li-ion battery cell essentially consists of anode, cathode, separator, electrolyte and a packaging. There are several types of commercial anode and cathodes materials which has different properties in terms of performance and safety. Figure 5 shows an example of the relative large temperature differences due to the thermal runaway response for Li-ion cells with same physical size but with different chemistries.

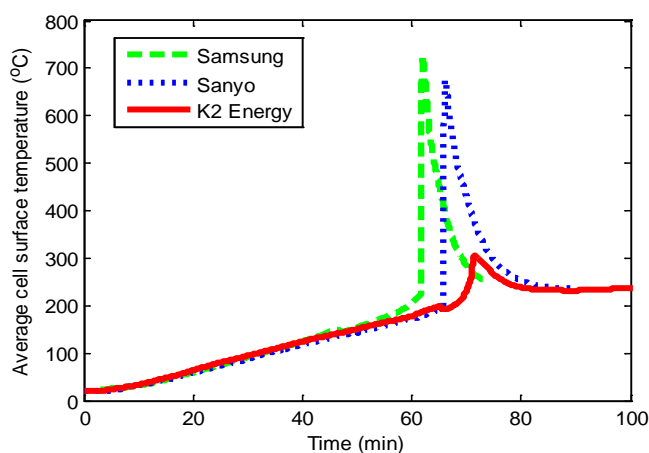


Figure 5. The battery cell surface temperature during external heating (oven) abuse test, showing the temperature rise upon external heating and the rapid temperature peak due to thermal runaway for two types of cobalt based cells (Samsung and Sanyo) and for a lithium iron phosphate cell (K2 Energy). All three cells are of the 18650 type. Reprinted with permission of F. Larsson [3].

In case of cell overheating, the polymer separator typically melts at temperatures ranging between about 130-160 °C [4]. Without the separator there will be an internal short circuit of the battery cell, which will discharge its electrically stored energy capacity and will heat up the cell and the adjacent cells and structures in the battery pack by Joule heating. The electrical energy released is typically less than the combustion energy of burning of the battery cell. There are limited measurements available, but the chemical energy can be about 5-20 times the electrical energy [5,6].

The electrolyte in Li-ion batteries consists of a Li-ion salt solved in a flammable solvent. This solvent has a boiling temperature in the range of 90-160 °C and any heating up to these temperatures will cause the solvent to evaporate. This causes the cells to swell and eventually the solvent will be released out of the cell, either because the cell is venting through the cell safety vent or the cell bursts.

The gases are either emitted as the organic solvents themselves such as dimethyl carbonate (DMC), diethyl carbonate (DEC), ethylene carbonate (EC) or decomposed into other gases such as CO, H₂, CH₄ etc. or blends of these gases. There is still only limited research available on the gases emitted from Li-ion batteries upon abuse situations. The gas emissions from Li-ion battery cells or fires are toxic, and contains e.g. hydrogen fluoride (HF) and other fluorine gases [5,6,7,8,9,10]. The fluoride gases originate from fluorine sources in the Li-ion cell; e.g. the Li-salt, typically LiPF₆, from additives containing fluoride and from the use of PVdF binder in electrodes. The gas emission most studied is hydrogen fluoride (HF) which is known to be very toxic, acid and highly corrosive. For other gases, e.g. phosphoryl fluoride (POF₃) there is no toxicity data available but it is at least a pre-cursor to HF.

The released gases can either ignite immediately upon release, causing a flare which potentially can heat up other cells such that they are forced into thermal runaway. Alternatively, the gases can be ignited at a later stage, possibly causing a gas explosion. Most hydrocarbons such as the solvents in Li-ion batteries have a lower flammability limit of about 50 g/m³ (a few vol%) Upon ignition the gas-mixture expand about 5-8 times. This means that 5 kg of electrolyte can form a flammable mixture having a 100

m³ volume. Upon ignition, it will expand to about 500 m³ causing an overpressure of 5 bars if contained in a sealed volume.

The probability for a single Li-ion cell failure, “field failure”, based on numbers of produced cells compared to numbers of reported fire failures, is typically about 1 ppm for cells (1 cell failure in 1 million cells) [11,12,13]. However, the statistics are not well reported. For a large battery pack, the mathematical probability for a single cell failure to occur within that pack will increase, simply because of the increased number of cells. Today there are no commercially intrinsically safe Li-ion battery cells, so single cell failures will continue to happen. Instead focus should be on mitigating the consequences of a single cell failure by proper battery system design in order to hinder or delay cell-to-cell propagation [14,15,16]. Cell-to-cell propagation and/or module-to-module propagation can be minimized through battery design by e.g. dividing the battery system into multiple compartments/modules or cell/module separation. The active and passive cooling systems and the integration of the battery system within the vessel also affect the risk for propagation.

It is typically difficult to stop and cool down a thermal runaway cell due to limited access to cool the cell surface. In case the fire has spread it can take a long time to cool down the battery, e.g. up to 24 hours. It is essential that the system and installation is designed to handle this situation.

5 Regulations, rules and guidelines

All ships are required to apply safety regulations and standards. What regulations to apply depend on the ship type and trade area. There are three main categories of ships: ships with international certificates (hereafter called SOLAS-ships), ships with national certificates and pleasure vessels. SOLAS-ships consist of cargo ships above 500 gross tons and passenger ships. Ships with national certificates are of all sizes and include also smaller vessels on international voyages.

5.1 International regulations

The international regulations consist of conventions, resolutions, codes and circulars issued by the International Maritime Organization (IMO) and ratified through national regulations. In general, the conventions only contain the main requirements while the technical details are found in different codes, e.g. the Fire Safety Systems code and the Fire Test Procedures code.

Regulations regarding electric installations are primarily found in the SOLAS convention. However, since the number of ships with large battery installations used for propulsion is relatively small, specific regulations for battery installations have not yet been developed by IMO. The available requirements for electric installations in different parts of the regulations shall or could still be applied to battery installations.

SOLAS II/1 Part D Electrical installations Regulation 45 provides a number of requirements regarding normal precautions against shock, fire and other hazards of electrical origin. There is also one paragraph related to batteries: *“9.1. Accumulator batteries shall be suitably housed, and compartments used primarily for their accommodation shall be properly constructed and efficiently ventilated.”*

Another important requirement is found in regulation 40.2 stating that the Administration shall take appropriate steps to ensure uniformity in the implementation and application of the provisions of this part in respect of electrical installations. A footnote is included which refers to the recommendations published by the International Electrotechnical Commission and, in particular, Publication IEC 60092 - Electrical Installations in Ships.

Footnotes in SOLAS are not mandatory and it is up to each nation's Administration to decide on its application. Furthermore, all international conventions (e.g. SOLAS) need to be incorporated into the national legislation to be put into force, e.g. Sweden has put this requirement into force through the regulation TSFS 2014:1 where it is required (Chapter 3 regulation 18 §3) that SOLAS ships shall fulfil a recognized classification society's rules and IEC 60092.

SOLAS chapter II-2 contains the regulations about fire safety. Regulation 4 “Probability of ignition” covers the risk of ignition and in one of its purpose statements it is stated that “ignition sources shall be restricted”. However, there are no requirements in the regulation that regulates how this shall be achieved with regard to battery installations.

Furthermore, most of the regulations in chapter II-2 have general requirements in their purpose statements that could be applicable to battery installations without having detailed requirements e.g. regulations 5, 6, 7, 8, 9, 10. Hence, at present, the safety of batteries is not included in international regulations but left for the classification societies to handle.

In regulation II-1/3-1 it is required that, in addition to the requirements contained elsewhere in the present regulations, ships shall be designed, constructed and maintained in compliance with the structural, mechanical and electrical requirements of a classification society or with applicable national standards of the Administration which provide an equivalent level of safety.

Consequently, it is not mandatory according to SOLAS to have a ship classed by a classification society. However, it is required by most Administrations that ships electrical systems shall be designed according to the requirements of a classification society (and classed). If not, the system shall be designed according to a national standard giving the same level of safety. Since the requirements of different classification societies differ somewhat it cannot be assumed that all ships fulfil similar requirements, even if it is likely that most ships comply with IEC 60092.

5.2 Classification rules

All SOLAS-ships are required or could be expected to be designed, constructed and operated according to the rules of a classification society. There are some major classification societies that dominate but there are also a large number of smaller ones. In this report we will focus on the largest classification societies and describe the rules available from some of them.

5.2.1 DNV GL

DNV GL has comprehensive rules and guidelines for battery installations. They have two additional class notations regarding batteries which are described in “Part 6 Chapter 2 Section 1 Battery Power” in their rules for classification of ships. The notations are denominated “Battery Power” (propulsion) and “Battery Safety” (over 50 kWh except Lead-acid and NiCd batteries).

The additional class notation Battery Power is mandatory for vessels where the battery power is used as propulsion power during normal operations, or when the battery is used as a redundant source of power for main and/or additional class notations. The first requirement is that when the main source of power is based on batteries only, the main source of power shall consist of at least two independent battery systems located in two separate battery spaces.

Further there are requirements for monitoring and managing the batteries with an Energy Management System. The state of charge (SOC) and state of health (SOH) of

the batteries shall also be monitored. Finally it is required that operating instructions (including charging procedures) shall be kept on board.

The additional class notation Battery Safety is mandatory for vessels where the battery installation is used as an additional source of power and has a capacity exceeding 50 kWh. Battery installations exceeding 50 kWh with lead-acid and NiCd batteries are excluded from this notation and these installations shall instead fulfil the requirements in Part 4, Chapter 8 "Electrical installations". The Battery Safety notation includes a number of requirements.

It is required that the battery spaces shall have structural integrity equivalent to the vessels structure. Additionally, the fire integrity shall be equivalent to spaces classed as other machinery spaces in II-2/9.2.2 with some additional requirements.

The environment within the space shall be monitored and controlled both with regards to temperature and explosion risk (depending on battery chemistry). A conventional smoke fire detection system is required but it is also recognized that the battery management system (BMS) is the primary indicator of incidents which may lead to possible overheating and fire.

A water-based fixed fire-extinguishing system is required although this requirement could be overridden depending on the type of batteries. Other types of fire extinguishing systems may be required depending on the battery manufacturers recommendations. In order to find out if this is the case a safety assessment needs to be carried out.

A safety assessment shall include:

- a) An identification of hazards (a list of all relevant accident scenarios with potential causes and outcomes);
- b) an assessment of risks (evaluation of risk factors);
- c) risk control options (devising measures to control and reduce the identified risks); and
- d) actions to be implemented.

The safety assessment is normally undertaken by the ship designer since it should take into consideration both hazards associated with the batteries and hazards from and to the rest of the ship e.g. fire, water ingress and loss of power. It is essential that all possible hazards from the actual batteries in use are identified. Information about these is to be provided by the battery manufacturer in the form of a safety description. A safety description shall cover all potential hazards represented by the type (chemistry) of battery and shall also propose a suitable fire extinguishing method.

Finally DNV GL has a section with additional requirements for "Lithium batteries" and systems. These requirements includes: Battery Management System, Battery alarms, Safety functions, Materials, Ingress protection, Safety description and Testing. The section about testing covers the batteries properties and the battery management systems.

5.2.2 Lloyds Register of Shipping

Lloyds Register of Shipping (Lloyds) has not developed any specific rules for battery installations other than lead-acid and NiCd batteries. Where other chemistries are to be used, the “LR ShipRight Procedure Assessment of Risk Based Designs” is to be followed (Part 6 Ch 2 sec 12). This procedure is a generic risk analysis procedure, refer to Figure 6, which could be used for any type of equipment or design that does not fulfil the rules or in case the rules do not contain any specific requirements. The process is risk based and it could be expected that with regards to batteries the outcome will be very similar to the safety assessment that DNV GL requires.

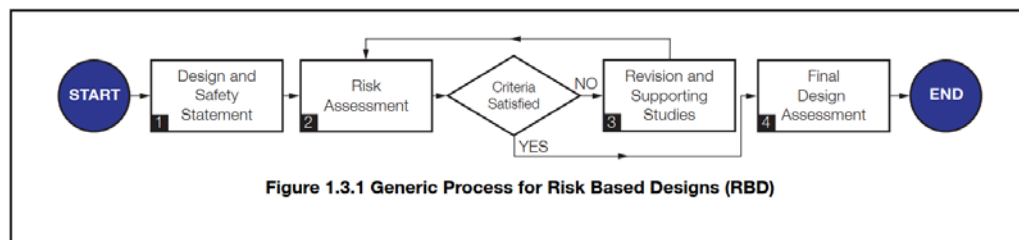


Figure 6. The generic process for risk bases designs provided by Lloyds Register of Shipping.

Lloyds have chosen to have rather general advice in order to allow for new solutions. They do have a “Guidance note for Battery Installations” which provides valuable information about battery installations on ships. The Guidance note is dated January 2016. However, the part that covers fire and fire safety is not completely up to date with present knowledge on Li-ion batteries. It has been mentioned that the document has been withdrawn and that a risk analysis should be conducted instead, but the document is still available on the website. Lloyds also brings forward a document “Large battery installations” dated January 2015 which has similar drawbacks as the “Guidance note for Battery Installations”. The document “Provisional Rules for Direct Current Distribution Systems” includes functional, performance and verification requirements on the DC system. Fire precautions are, however, not included in this document.

5.2.3 Bureau Veritas

Bureau Veritas (BV) has an additional class notation for battery systems (Steel ships Pt E, Chapter 10, Section 21) which may be assigned to ships when batteries are used for propulsion and/or electric power supply purposes during operation of the ship. This notation is mandatory when the ship is only relying on batteries for propulsion and/or electrical power supply for main sources.

Battery systems -Steel ships Pt E, Chapter 10, Section 21 lists the documents to be submitted for classification and gives definitions for BMS etc.. It also has requirements for ventilation, both for large vented batteries such as lead acid but also for batteries that can create explosive atmospheres and for toxic gases. For water entry the requirements are that sea water should not be able to enter the battery compartment

and for liquid leakage no piping except that needed for the battery is allowed in the battery compartment, however, exceptions can be made if one has efficient detection of fluid leakage etc. The batteries, including connections and cooling system, should be protected from falling objects by Access hatches. The battery room should be painted with antistatic painting to protect against electrostatic hazard. The battery pack should have protection against ingress, IP 2X for less than 1500 VDC (voltage direct current) and IP32 for more than 1500 VDC.

The battery compartment boundaries are to be fitted with the thermal and structural subdivision corresponding to “Other machinery spaces”. A0 boundaries are to be fitted as a minimum between two adjacent battery compartments.

The battery compartment is to be fitted with a fixed gas fire-extinguishing system according to Part C, Chapter 4. The gaseous agent that is used should be compatible with the technology of the battery employed. When lithium batteries or other chemistries are used the suitability of fire-extinguishing system to battery type should be documented.

For lithium type batteries and other types of batteries which may be accepted by the Society, a risk analysis covering battery packs, battery compartment and BMS is to be conducted and submitted to the Society for review.

The following items, at least, are to be covered in the analysis:

- Risk of thermal runaway.
- Risk of emission of combustion gases.
- Risk of internal short-circuit.
- Risk of external short-circuit.
- Risk of sensor failure (voltage, temperature, gas sensor).
- Risk of high impedance (cell, connectors, etc.).
- Risk of loss of cooling.
- Risk of leakage (electrolyte, cooling system).
- Risk of failure of BMS (error on manoeuvring breakers, overloading, over discharge).
- Risk for external ingress (fire, fluid leakage, etc.).

Battery systems -Steel ships Pt E, Chapter 10, Section 21 also contains requirements on certification process for batteries stating that “The cells should be type approved according to scheme H_{BV} as described in NR320” and that prototype tests of cells should be conducted according to a National or International standard or, in lieu of such standard, the manufacturers specification. It should include behaviour of the cell when the battery is getting out of specification (high, low tension etc.). A manufacturer certificate is required.

Also the battery pack and its BMS “should be approved according to scheme I_{BV} in N320”. Prototype tests should be conducted according to a National or International standard or, in lieu of such standard, the manufacturers specification. It should include at least ability to achieve safety functions, proper working of alarms, functions and monitoring systems, IP, optimized battery life etc. Tests of similar type are then also to be conducted on board. A product certificate of the Society is required.

Factory acceptance tests should be conducted according to a National or International standard or, in lieu of such standard, the manufacturers specification. It should include

at least ability to achieve safety functions, proper working of alarms, functions and monitoring systems, insulation and IP characteristics.

Onboard tests are also to be conducted for fire detection, dangerous gas detection, fire extinguishing efficiency and accessibility of battery compartment. For dangerous gas it is specified that the testing includes testing of the positioning of the detectors to detect dangerous gas concentration in any normal circumstance of ventilation system. For Fire extinguishment it is stated that gas concentration after fire extinguishing system operation should be measured and be high enough to prevent an explosion or stop a fire.

5.3 National regulations

5.3.1 Sweden

Commercial ships not required to have international certificates will have national certificates. In Sweden, the national regulations have been similar to the SOLAS requirements from the respect that there were no specific guidelines regarding battery installations but there are a number of more general guidelines regarding electrical installations and fire safety measures that could be applied.

However, in 1 of June 2017 a new ordinance entered into force which is applicable to all passenger ships and all other ships above 5 m, except ships with international certificates, ships with EU certificates (passenger ships, fishing boats and inland waterway vessels), pleasure vessels less than 24 m, existing pleasure vessels less than 100 gt and naval ships.

This ordinance is based on functional requirements and it has been divided into three levels. The first level is the regulations which consists of mandatory requirements. Regarding battery installations, the requirements are:

Own translation of Swedish original text:

6 § Batteries shall be located, stored and mounted in such a way that they do not risk being damaged or that they could cause damage. Spaces where batteries are located shall be sufficiently ventilated. Batteries shall be monitored as necessary.

Swedish original text:

6 § Batterier ska vara placerade, stuvade och monterade på ett sådant sätt att de inte riskerar att skadas eller att skada omgivningen. Utrymmen där batterier är placerade ska vara tillräckligt ventilerade. Batterier ska vara övervakade i den omfattning som är nödvändig.

The second level consists of general advice (Allmänna råd) which should describe the generally accepted way of fulfilling the regulation or at least the Administration's view. It is not necessary to fulfil the requirements in line with the general advice. In fact, one

may do whatever one like as long as one could show that the solution gives an equivalent level of safety as the accepted (the general advice).

Own translation of Swedish original text:

General advice

Special consideration should be given to monitoring, ventilation and cooling of batteries designated for the ships propulsion and to large battery installations.

Swedish original text:

Allmänna råd

Särskild hänsyn bör tas till övervakning, ventilation och kylning av batterier som är avsedda för fartygets framdrivning och av stora batterianläggningar.

Finally, the third level consists of complementary information. This is not included in the ordinance but is instead described in a webpage at the Swedish Transport Agency. The complimentary information is advice on things that may need to be considered depending on the particular installation on a specific ship.

In the case of battery installations larger than 20 kWh it could be suitable to consider:

- *During design. The batteries chemical and physical design and risks regarding overheating, fire and production of smoke and flammable gases.*
- *The battery spaces – are these adapted and suitable?*
- *The number of air changes and the fire safety of the ventilation system – does it need to be adapted to the specific type of batteries?*
- *The risk of heat production – is it minimized by e.g. cooling or monitoring of the battery cells?*
- *The system – is it constructed in a robust and failsafe way ensuring that a single failure or short cut does not take out the whole system?*

För stora batteripack överstigande 20 kWh är det lämpligt att beakta följande:

- *Vid planering, batteriernas kemiska och fysikaliska konstruktion och riskfaktorer beträffande överhettning, brand, rökutveckling och utveckling av brandfarliga gaser.*
- *Utrymmena där batterierna installeras – är dessa utrymmen anpassade och ändamålsenliga?*
- *Antalet luftväxlingar och ventilationssystemets brandsäkerhet – behöver dessa anpassas till den aktuella batteritypen?*
- *Risken för värmeutveckling – är den minimerad genom t.ex. kylning eller övervakning av battericeller?*
- *Systemet – är det byggt på ett robust och felsäkert sätt så att enstaka fel eller kortslutning inte slår ut hela systemet?*

The Swedish text is shown as reference. It is clear that the approach with the new regulations is performance based and that it is up to the ship owner (or probably the designer) to find a safe design of the battery installation. The text in the regulation is rather general and does not give any details about how to design a Li-ion battery

installation. Unfortunately, also the general advice is very unspecific, which is not in line with the Transport Agency's explanation about how a general advice shall be written. However, the Transport Agency has chosen to have a rather general text here in order to allow for innovations. Normally when a new ship is built or re-designed for battery propulsion the Transport Agency requests a risk analysis, this is decided as an outcome of the initial new construction/redesign meeting.

The complimentary information gives some advice about topics to consider during the design of the system but it does not give all necessary information, e.g. in this case the risk of explosive gases is not mentioned. As a consequence, it will be difficult to design a battery installation and be confident that it fulfils the requirements.

National ships with international or EU certificates shall be classed or adhere to the rules of a classification society. This causes a problem for the smaller ships since it could be costly and even difficult for a small ship to fulfil the present class rules.

5.3.2 Norway

In Norway, there are several ships with battery installations and Norway has issued a Circular about battery installations (RSV 12-2016). This is applicable for Li-ion or similar battery technologies and for all ships except non-commercial ships below 24 m in length. The circular deals primarily with tests on the battery installations. It is also required that the installation shall be approved by a classification society.

The circular states that the company should describe their philosophy regarding design and location of battery spaces, explosion relief, as well as ventilation and fire-extinguishment based on the battery technology used. Air extracted from ventilation of battery modules and battery spaces should be carried to areas where it can do no harm and only equipment associated with the battery should be placed in the battery room.

In order to identify the damage potential of a possible thermal runaway event in a specific battery system, circular V requires that testing should be carried out on both cellular, modular and system level. The results from the tests are then used to determine the design of battery spaces with associated systems for fire extinguishment, explosion relief, ventilation, etc.

The required tests include a propagation test that evaluates the possibility for a thermal runaway to spread between modules. The requirement is that it should not spread. A gas analysis is also required to be done on a cell heated until it vents in an inert atmosphere. Finally, an explosion analysis shall to be conducted based on the gas analysis from one cell extrapolated to an entire module. If the module is designed so that no spread of thermal runaway occurs between cells, then the explosion analysis can be conducted on one cell.

For battery systems below 20 kWh, no tests are required but only a risk analysis.

5.4 Standards

There are different standards available that deal with batteries and testing of batteries. However, since most regulations do not contain detailed requirements about batteries these standards are not referred to except within the rules of some classification societies. The IMDG code (transport of dangerous goods) do also require that batteries being transported on ships shall fulfil UN 38.3. Standards that are (or could be) relevant include:

- UN 38.3 Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria as referred to by IMDG code ch 2.9
- EN/IEC 61508 Functional safety of electrical/electronic/programmable electronic safety-related systems
- IEC 62619 Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications
- EN/IEC 62281:2012. Safety of primary and secondary lithium cells and batteries during transport
- EN/IEC 62620 Secondary cells and batteries containing alkaline or other non-acid electrolytes –Secondary lithium cells and batteries for use in industrial applications
- EN IEC 62281 Safety of primary and secondary lithium cells and batteries during transport

UN 38.3 contains requirements for batteries during transport. These requirements are on batteries that are in storage and not in use and should be considered as a minimum safety level. It is however important to note that these tests do not say anything about the safety of the battery in use.

The EN/IEC 61508 series contain requirements on electrical, electronic and programmable electronic safety related systems. It does not contain specific battery requirements but treat these systems generally describing risk levels and safety integrity levels that should apply depending on risk level, documentation that should be supplied etc.

IEC 62619 gives advice on general safety considerations such as wiring, venting, temperature and voltage measurements, terminal contacts, assembling and design, operating range and quality plan for batteries to be used in industrial applications. It contains also tests to be conducted on cells or battery. The tests covered are:

- External short circuit on cell
- Impact test on cell
- Drop test on cell and battery
- Thermal abuse on cell
- Overcharge on cell
- Forced discharge on cell
- Internal short circuit on cell
- Propagation test on battery
- Overcharge control of voltage on battery
- Overcharge control of current on battery
- Overheating control on battery

EN/IEC 62620 contains information on marking of cells and measuring different parameters during normal use such as rating and internal resistance

EN/IEC 62281 concern safety during transport and includes the same tests as UN 38.3.

5.5 Regulations and recommendations for on-shore premises

It is only recently that one has started to introduce chemical energy storage including Li-ion batteries also in buildings. As the situation in buildings is in some extent similar as in ships, it is worthwhile to also study work and advice available for on-shore premises.

5.5.1 Loss prevention recommendations in FM Global Property Loss Prevention Data Sheets 5-33

FM DS 5-33 [17] contains loss prevention recommendations for the design, operation, protection, inspection, maintenance and testing of on-shore electrical energy storage systems that use Li-ion batteries. Electrical energy storage systems are typically installed within a building or outside a building within a dedicated enclosure.

The construction and the location of electrical energy storage systems is an essential part of the overall fire protection concept. If located outside of a building, it is recommended that the electrical energy storage system should be away from critical buildings or equipment. If the space separation between electrical energy storage system enclosures is less than 6 m, a thermal barrier rated a minimum of one hour should be installed on the inside or outside of the enclosure. Enclosure vents or other penetrations (if used) should be arranged and directed away from surrounding equipment and buildings.

The document provides technical support for the recommendations described above. If being constructed of steel or other metal, the enclosure will conduct heat and radiate it away from the enclosure. A substantial amount of radiation and conduction through the metal sides of the enclosure could potentially ignite a fire in adjacent enclosures if not separated by the recommended distance.

Electrical energy storage systems installed within a building should be located in a dedicated enclosed room that is accessible for manual fire-fighting operations. The enclosure should have a thermal barrier rated a minimum of one hour.

An automatic sprinkler system should be provided within the battery storage system enclosure (irrespective if the enclosure is outside or within a building). The system should be designed for a discharge density of 12 mm/min over 230 m² or the enclosure area, whichever is smaller. The battery storage enclosure should also have a smoke

detection system and portable fire extinguishers should be provided inside the enclosure.

5.5.2 Recommendations by DNV GL for on-shore

A comprehensive report by Hill [18] issued by DNV GL summarizes the main findings and recommendations from an extensive fire and extinguisher testing program that evaluated four different Li-ion chemistries, a lead-acid battery and a vanadium redox battery. The objective of the work was to address code and training updates required to accommodate arrangement of energy storage in New York City. The main conclusion from the report is that the installation of electrical energy storage systems into buildings introduces risks. However, these risks are manageable within existing building codes and fire-fighting methods when appropriate conditions are met.

In the case of heating by fire or thermal abuse all batteries that were tested emitted toxic gases. This can however be expected from most fires. The toxicity of the battery fires was found to be mitigated with ventilation rates common to many occupied spaces. The batteries exhibited complex fire behaviours that required large quantities of water to be used for fire-fighting. But it was found that the fire-fighting requirements need not be excessive if an intelligent, system-level approach is taken that includes external fire ratings, permits direct water contact of the cells and implements internal cascading protections.

Four different Li-ion chemistries; lithium titanium oxide (LTO), lithium iron phosphate (LFP), nickel manganese cobalt (NMC) and bio-mineralized lithium mix-metal phosphate (BM-LMP), lead acid and vanadium redox batteries represented by nine unique battery types from eight different manufacturers were tested.

The capacity size of the tested cells ranged from 1.2 to 200 Ah with an average of 52 Ah. All cells were heated with 4 kW of radiant electric heat and were placed inside a small chamber (sized 760 mm by 760 mm by 760 mm) and exposed to heat until they vented. For the fire suppression tests, the abuse chamber was fitted with a 9.5 litre water container. The container was pressurized and had an in-line electronic solenoid valve for activation. Once a single temperature measured on the outside of a cell exceeded 350°C, the solenoid was opened and the extinguisher released. The container was typically filled with 3.8 liter (1 gallon) of liquid and the whole container was emptied. A fogging water mist nozzle was fixed approximately 250 mm to the side of the battery cell and about 75 mm above. The container pressure was 5.2 bar. During the fire suppression tests, all cells had a 90% SOC.

Battery modules were tested in a partially enclosed outdoor burn facility. The module sizes ranged from 7.5 to 55 kWh. Burns were conducted directly with a propane torch. A steel grate was hung from the ceiling of the enclosure at a height of approximately 1.2 m from the floor. Below the grate a tray was constructed to collect water runoff. Two sprinkler heads were installed above the burn location and were fed from a hydrant.

The following fire extinguishing agents were tested in the small-scale cell fire tests and in the larger module fire tests:

- Water
- Pyrocool. According to its manufacturer, Pyrocool is a multipurpose fire-fighting foam concentrate that is mixed with water to provide improved performance for Class A, Class B and Class D fires.
- F-500. According to its manufacturer, F-500 is an 'encapsulator agent' that is mixed with water in concentrations between 0.5% to 3% to provide improved performance for Class A, Class B and Class D fires.
- FireIce. According to its manufacturer, FireIce is a gel that encapsulates and creates a safety barrier around the fire source.
- An aerosol agent

It was observed that the most challenging aspect of the battery fire is its deep-seated nature. Therefore, access to the heat source is necessary to provide adequate cooling and continuous cooling is required after the flames have been knocked down, in order to contain the fire. The tested agents (as per the list above) proved to be slightly less effective than water at cooling of individual cells in the small-scale tests. On the battery module tests, there was no evidence that the agents performed better than water. Hill [18] states that, although water proved most effective for cooling, water and any water-based agent could introduce shorting risks when applied on a full system. This may worsen the situation in addition to presenting a collateral damage risk. Forced access through cutting or similar activities to the interior of battery systems may be difficult or inadvisable for first responders as this has proven to produce sparks and short circuits. In this case, water should be used to provide indirect cooling on the outside of the system to prevent spreading.

Water use inside the system should be done with care to avoid shorting adjacent, non-fire involved cells, i.e., the failing module should be isolated and targeted. Fully involved systems may be fire damaged enough to allow better water penetration. Suppression of large, fully involved systems may take more time than fires of similar size with different fuels. It is therefore recommend that fire service personnel continue to suppress with water for as long as required and then ensure the system is fully cooled throughout when suppression appears complete.

As many encapsulating agents, including foam (AFFF) are intended to blanket the fire and a battery fire needs to have heat removed as quickly as possible, DNV GL generally do not recommend the use of foam for electrical energy storage systems fires. Foam and some of the tested agents encapsulates the fire and insulate surrounding areas from heat. In an exothermic battery fire, trapping heat is undesirable. According to the source, this is in line with experience from testing in other projects and from use in actual fires. Because the consumption of a single Li-ion cell is rapid, the metal fire fuels (Class D fires) are quickly consumed and the fire evolves to a Class A, B or C fire. Therefore, DNV GL does not either see an advantage to using a Class D fire extinguisher on a single cell or system fire.

The pyrotechnically generated aerosol that was tested proved effective at knocking down flames and gaseous agents may suppress the flammability of contained atmospheres with high explosive gas content. But in the case of severe fires in electrical energy storage systems, where these agents would be tasked to suppress flammability, Li-ion cells may be producing heat above the auto-ignition temperature of the flammable gases. This may result in fire, if oxygen were reintroduced to the system.

Therefore, DNV GL recommends gas-based systems be backed up by water-based suppression when cooling becomes a necessity, in combination with cascading protections in the battery modules and battery system.

It was observed that the remaining heat between batteries can lead to delayed cascading and prolonged extinguishment times for battery modules which illustrates the importance of cascading (propagation) protections between cells and inter-cell cooling in battery modules. DNV GL recommends more stringent criteria such that a single cell failure cannot propagate to adjacent cells, with the intent of maintaining heat release rates that can be managed by the water extinguisher flow rate and the system external fire rating. This recommendation shows that the fire suppression solution and the module design are interlinked; a module with an adequate cascading protection is more likely to be appropriately designed with a gas-based fire suppression system. If a fixed suppression systems is installed in an enclosed environment containing the single failed Li-ion battery cell, it may suppress flammability in the enclosed space. The use of water may be unnecessary at this point unless the fire has progressed.

Although the use of water demonstrated excellent cooling capability, water could potentially short-circuit undamaged cells or adjacent modules. The use of water is a fully committed extinguishing tactic that is highly likely to result in a total loss of the asset. Because it was noted that the aerosol test demonstrated extinguishment of the fire upon execution, aerosols can potentially serve as an initial attack for the fire followed by water as a backstop.

In conclusion, DNV GL recommends the following based on their experience:

Stage 1: If a battery system is designed to limit cell cascading, a gas based fire suppression system may be considered for the first stage of fire-fighting, in order to extinguish a single cell fire and prevent flashover in a contained environment.

Stage 2: If temperatures continue to rise or if an increasing level of smoke and gas is detected, forced ventilation (of the enclosure containing the batteries) and fire-fighting using water should be considered to cool the battery system and prevent further propagation of fire.

Stage 1 provides an opportunity for avoiding collateral damage and total asset loss. Stage 2 provides a backstop for a situation when more than one battery cell is on fire. Both stages may also include some form of alarm or notification external to the battery system that notifies first responders of elevated risk.

6 Fire safety systems on board ships used today

There are today many different fire safety measures used on board ships, an overview of them is given here.

6.1 Fire detection systems

Detection and alarm is covered in SOLAS chapter II-2, regulation 7. The regulation includes requirements for fixed fire detection and fire alarm systems, manually operated call points and fire patrols. Depending on the classification of a space the requirements for fire detection varies. It is not defined in SOLAS how to classify a battery space. DNV GL requires that it should be classified as a machinery space. In that case it is required that a fire detection system shall be installed. There are a number of requirements on the detection system in SOLAS, some of the more important are as follows:

The function of the detection system under variations of ventilation shall be tested after installation. Furthermore, the function of the system shall be periodically tested with appropriate hot air, aerosol particles or other phenomena to which the detector is designed to respond.

For detailed requirements on system performance, regulation 7 refers to the Fire Safety System (FSS) Code. Fire detection and alarm systems shall comply with chapters 9 and 10 of the FSS Code. Chapter 9 manages point heat detectors and smoke detectors and chapter 10 manages sample extraction smoke detection systems (aspirated smoke detection systems).

The system and equipment shall be appropriately designed to withstand difficult operational conditions like supply voltage variation and transient, ambient temperature changes, vibration, humidity, shock, impact and corrosion normally encountered in ships. Furthermore, at least two power sources shall exist to power electrical equipment used for fixed fire detection and fire alarm system. One of these should be an emergency power source.

Detectors are required to be activated by heat, smoke or other products of combustion, flame, or any combination of these factors. Detectors that will be activated by factors of incipient fires may be considered, provided that they are no less sensitive than detectors activated by products. Flame detectors shall only be used in addition to smoke or heat detectors. All detectors should, however, be of a type such that they can be tested for correct operation and restored to normal surveillance without the renewal of any component. DNV-GL requires conventional smoke detection for battery spaces.

With regards to the positioning of the detectors it is required that they shall be located for optimum performance. Position close to beams and ventilation ducts where patterns of airflow could adversely affect the performance should be avoided. Positions where impact or physical damage is likely should also be avoided. The maximum

spacing of detectors is shown in Table 2. Exceptions may be made if based on test data which show the characteristics of the detectors.

Table 2 Spacing of detectors according to the FSS Code.

Type of detector	Maximum floor area per detector [m²]	Maximum distance apart between centres [m]	Maximum distance away from bulkheads [m]
Heat	37	9	4.5
Smoke	74	11	5.5

The activation of any detector or any manually operated call point shall start an audible and visual fire signal at the control panel and indicate the activated unit. If the signals not have received attention within two minutes, an audible alarm shall be automatically sounded in the crew accommodation, service spaces, control stations and machinery spaces. The control panel should also give an audible and visual false signal in case of power loss or failure in electric circuits for the detection system.

6.2 Fire-fighting systems

Generally, SOLAS Chapter II-2, regulation 10 requires that a fixed fire-extinguishing system shall be installed on board ships and that fire-extinguishing appliances shall be readily available. Machinery spaces of Category A¹ containing internal combustion machinery shall be provided with a fixed fire-extinguishing system. Any of the three following types of systems may be used:

1. a fixed gas fire-extinguishing system,
2. a fixed high-expansion foam fire-extinguishing system, and
3. a fixed water-spraying system fire-extinguishing system.

When the fire-extinguishing medium is stored outside of the protected space, it shall be stored in a room, which is located behind the forward collision bulkhead. The storage room should not be used for any other purposes and the entrance to the room shall preferably be from the open deck and shall be independent from the protected space. If the storage room is located below the open deck, it shall be located no more than one deck below the open deck and shall be directly accessible by a stairway or a ladder from the open deck.

For passenger ships of 500 gross tonnage and above, and cargo ships of 2000 gross tonnage and above, Machinery spaces of category A, in excess of 500 m³, shall in

¹ Machinery spaces of category A is defined as those spaces and trunks which contain either:

1. internal combustion machinery used for the propulsion;
2. internal combustion machinery used for purposes other than main propulsion where such machinery has in the aggregate a total power output of not less than 375 kW; or
3. any oil-fired boiler or oil fuel unit, or any oil-fired equipment other than boilers, such as inert gas generators, incinerators, etc.

addition to the 'total flooding system', be protected by an approved type of water-based or equivalent local application fire-extinguishing system. Such systems shall comply with the installation guidelines, component tests and fire test procedures in MSC/Circ. 913 as amended by MSC/Circ. 1082.

The activation of the local application fire-extinguishing system should not require the engine shutdown, closing of fuel tank outlet valves, evacuation of personnel and sealing of the space. Any of these actions would lead to loss of electrical power or reduction of manoeuvrability.

6.2.1 Fixed gas fire-extinguishing systems

Where a fixed gas fire-extinguishing system is used, openings, which may admit air to enter, or allow gas to escape from, a protected space shall be capable of being closed from outside of the protected space, according to the requirements in SOLAS Chapter II-2.

Detailed installation requirements for fixed gas fire-extinguishing systems are given in Chapter 5 of the FSS Code. Fixed gas fire-extinguishing system equivalent to systems specified in the FSS Code may be used. Such systems shall comply with the installation guidelines, component tests and fire test procedures in MSC/Circ. 848. The installation requirements for such equivalent systems are in similar to the requirements in Chapter 5 of the FSS Code.

In addition, approved fixed aerosol fire-extinguishing system may be used. Such systems shall comply with the installation guidelines, component tests and fire test procedures in MSC/Circ. 1007.

6.2.2 Fixed high-expansion foam fire-extinguishing systems

Detailed installation requirements for fixed high-expansion foam fire-extinguishing systems are given in Chapter 6 of the FSS Code.

6.2.3 Fixed water-spraying system fire-extinguishing systems

Water pumps, other than those serving the fire main, required for the provision of water for fire-extinguishing systems, their sources of power and their controls shall be installed outside of the space or the spaces protected.

Detailed installation requirements for fixed water-spraying fire-extinguishing systems are given in Chapter 7 of the FSS Code. These requirements stipulate that nozzles shall

be arranged such as to ensure an effective distribution of water of at least 5 (liter/m²)/min in the protected space. The system may be divided into sections and the distribution valves shall be operated from easily accessible positions outside the protected space.

The pump for the system shall be capable of supplying all sections simultaneously, at the necessary water pressure, in any one protected space. The pump shall be driven by independent internal combustion machinery. However, if the pump is dependent upon power being supplied from the emergency generator, the generator shall be so arranged that as to start automatically in case of main power failure so that the pump is immediately available. The independent internal combustion machinery for driving the pump shall be so situated that a fire in the protected space for spaces will not affect the air supply for the machinery.

Fixed water-spraying systems equivalent to systems specified in the FSS Code may be used. Such systems shall comply with the installation guidelines, component tests and fire test procedures in MSC/Circ. 668 / 728. The installation requirements for such equivalent systems are similar to the requirements in Chapter 7 of the FSS Code.

6.2.4 Fire-fighting equipment

Machinery spaces of Category A shall have at least one portable foam applicator unit complying with the provisions in the FSS Code. In addition, there shall be a sufficient number of portable fire extinguishers of the foam type. The extinguishers shall be located such that the walking distance to an extinguisher is maximum 10 meters.

No advice is given either in regulations or in the guidelines on portable extinguishers in battery rooms.

6.3 Fire Containment

The different class societies require that large batteries are installed in a dedicated battery space. The SOLAS convention is not precise when a separate battery space is required or not and accordingly, different Administrations may have different interpretation about this, e.g. Sweden requires a separate battery space when the battery capacity is larger than 20 kWh.

“SOLAS II-1/45.9.1. Accumulator batteries shall be suitably housed, and compartments used primarily for their accommodation shall be properly constructed and efficiently ventilated. “

In SOLAS, the fire integrity between different spaces is regulated by regulation II-2/9. All spaces are categorized according to their use and content, however battery spaces are not mentioned since they are relatively new. If it is difficult to categorize a space the category that is closest and gives the most stringent requirements shall be chosen. And finally it is up to the Administration to decide on the category for the space, unless the classification society has been given delegation to do this.

DNV GL is requiring that the battery spaces shall have structural integrity equivalent to the vessels structure, and that the fire integrity shall be equivalent to spaces classed as other machinery spaces in II-2/9.2.2 with some additional requirements.

The different types of fire divisions are tested in a fire test where a test furnace is heated according to a standard temperature curve and the divisions ability to prevent the spread of heat and hot gases is evaluated. The standard curve is based on the development of fires in normal (building) compartments. A thermal runaway in a Li-ion battery compartment may produce more severe conditions.

Another important aspect is that a thermal runaway often produces a directed concentrated flame that may heat the fire division in a small spot. In the fire test the division is heated uniformly over its whole surface. It is thus possible that a normal A-60 division may be penetrated by the flames relatively quickly and possibly well under the required 60 minutes.

6.4 Explosion protection

The gases from a venting Li-ion battery are flammable and there are thus a potential for explosion if these gases are ignited when gas has accumulated in the room. These risks can be handled by system design, i.e. minimizing the amount of gas that can be released by minimizing propagation between cells, minimizing risk of gas release, installation of a powerful ventilation system or design of explosion relief vents in the rooms to release the explosion in a safe way and direction.

These risks should be identified in the risk analysis that is required in the classification rules and possible safety measures shall also be proposed and installed. On board ships today these risks are normally taken care of by installing ventilation and requiring EX-classed equipment within the spaces, however in case of battery failures potential ignition sources are provided by the battery. There are usually no explosion protection systems on board ships except possibly in crankcases. There could however be similarities with low flashpoint fuels and there might be possibilities for advice from these designs.

6.5 Ventilation

There are today requirements for ventilation on onboard car decks in order to control flammable and toxic gases. There are also requirements for ventilation when dangerous goods are freighted.

7 Limitations of traditional fire safety measures

The fire safety measures used traditionally in engine rooms on board ships are designed to protect against non-gaseous releases of fuel, oil spills, etc. which makes the measures too slow to mitigate the consequences of a thermal runaway in most cases if they are activated after a cell has vented. Ships are normally not equipped with explosion suppression systems, explosion suppression could be needed if a large cell or several cells releases its contents and then are not ignited immediately but at a later stage. In addition are the extinguishing systems available not designed to mitigate the heating that is taking place in the actual cells. The measures do, however, protect the batteries from being heated from a fire external to the battery which is an important feature.

Traditionally, total flooding carbon dioxide (CO₂) systems have been used for the protection of machinery spaces and cargos holds on board ships; simply because it is the least costly alternative. Another advantage is that carbon dioxide can be used in both total flooding and local application system designs. The use of carbon dioxide systems has an advantage over halocarbon agents for applications with a deep seated Class A fire potential, like cargo holds. Another advantage relates to applications where decomposition of halocarbons would be problematical like in ovens or in applications where much agent is needed such as refrigerated, bulk storage. Furthermore, the design flexibility with selector valves and central storage are not available with the halocarbon agents. Neither inert gases nor the halocarbons are very effective on deep seated class A fires and none of the gaseous alternatives can be used in local application modes. The drawbacks with carbon dioxide include the system installation footprint and volume demand and the safety and health aspects [19]. There are few if any investigations available on carbon dioxide systems effect on fires in batteries. It can probably knock down the flames initially but maybe not provide enough cooling of the battery to prevent further thermal runaway. More data is needed in order to investigate this.

Inert gases work by reducing the oxygen concentration in the protected compartment to a point where it will not support a fire, but still high enough to support life. The essential design considerations for inert gas systems are therefore pressure venting and volume. It is important to design the system to achieve the correct concentration without reducing the oxygen concentration below life-threatening levels. Inert gas systems designed to concentrations above 62% (corresponding to 8% oxygen or below) shall be used only in unoccupied areas where personnel are not exposed to such oxygen depletion. Venting of inert gases is important as it displaces the air volume in the hazard area [20]. Inert gases do not cool the battery enough and also there is a potential for battery fires to produce oxygen on their own and therefore inert gases have very limited use on battery fires.

There are a number of advantages with water mist total compartment systems compared with the gaseous alternatives [21], including for example that:

- Water mist systems can be activated faster than a gaseous system, thus reducing fire damage, since it is not necessary to close openings and shut down ventilation before the start of discharge.

- Water mist has more attractive environmental properties than the halocarbon agents.
- Water mist does not present a life safety threat like carbon dioxide.
- The gaseous systems are usually limited to a single discharge of agent whereas most water mist systems have a virtually unlimited water supply.
- In high energy fire situations, the halocarbons can experience decomposition, thus creating hydrofluoric acid (HF) whereas decomposition of the water mist is not an issue.

The drawbacks of water mist for machinery space applications includes the fact the smaller fire (related to the volume of the protected compartment volume) may not be extinguished or the time to extinguishment can be very long. This is especially true for smaller fires that are 'hidden' by obstructions from the direct application of water [22]. On the other hand, smaller fires do typically not exhibit any thermal threat to the protected compartment or equipment [23]. Battery fires require a lot of cooling and traditional water mist system design is therefore probably not sufficient instead a higher water density is needed.

Although recognized by SOLAS as a prescriptive alternative, fixed water-spraying fire-extinguishing systems are not commonly used for machinery space applications, especially not after the introduction of water mist technology in the mid-1990's. The drawback compared to water mist technology for machinery spaces is the higher water flow rates. Although high flow rates and larger water droplets may provide improved cooling of the protected compartment or equipment, it could counteract fire extinguishment of small Class B fires as less water is vaporized by the fire [24]. The performance of a water spray system may, however, be improved by the use of a foam agent additive, particularly for Class B pool fire scenarios. Fixed water-spraying systems could, however, be an option for battery fires.

High-expansion foam systems may provide installation benefits over carbon dioxide systems for very large machinery spaces that would require huge quantities of carbon dioxide. An obvious advantage is that there are no acute health hazards with high-expansion foam. Traditionally, high-expansion foam systems are using air from outside of the protected compartment for the generation of foam. In that respect, it should be recognized that imbalances in the air pressure between protected area and the outside can have negative impacts on the production of foam. Therefore, pressure panels should be installed to retain the air pressure balance. There are systems that utilize the air in the protected spaces for foam generation, i.e. "inside air" systems. No air supply from the outside and no duct to transfer of the foam are required. Foam is generated by generators positioned inside the protected compartment providing an expansion ratio of around 650. The drawback of inside "inside air" systems is that the recirculation of hot combustion gases to the foam generators may degrade the quality of the foam and the effectiveness of these systems. Large fires, which produce large quantities of smoke and high temperatures, may therefore be a challenge for this type of high-expansion foam system [25]. There are very few studies available on the effectiveness of foam against battery fires. A drawback of the foam could be that it does not reach the actual cells and can therefore not provide direct cooling of the cells. There could, however, foam could potentially be introduced in the battery pack to provide

direct cooling. However, more test data is needed to confirm this. DNV GL do not recommend the use of foam as discussed in section 5.5.2 [18].

Pyrotechnically generated aerosols consist of a mixture of an oxidizer and a fuel. The oxidizer is an inorganic salt, typically the nitrate or perchlorate of either sodium or potassium. Once ignited by a suitable source, the oxidizer reacts with the fuel and in the process, generates salts of potassium or sodium, such as the chloride, oxide or hydroxide. As the pyrotechnic reaction is highly exothermic, the alkali metal salts are generated in gaseous form. As they cool and condense, they produce very small particles or aerosols, typically 1 micrometer in diameter [26]. Large-scale fire tests were conducted to identify the fire extinguishing capabilities and limitations of pyrotechnically generated aerosols in shipboard machinery space applications. A total of 18 tests were conducted utilizing the equipment from three manufacturers. It was observed that all three systems provided good capabilities against Class B fires but had difficulty extinguishing the Class A wood crib fires, unless the wood crib was ignited only two minutes prior to discharge of the system [27]. DNV GL included an aerosol system in their investigation [18] and came to the conclusion that the flames were knocked down, but with the agent did not cool the fire as efficient as water.

To summarize; in order to achieve protection of the battery compartment, there is probably a need for several systems; a system that protects against regular fires, a system to cool the cells and possible also an explosion suppression system.

8 Limitations of regulations and guidelines

The international regulations contain very few details on batteries and in particular Li-ion batteries used for propulsion. Instead the safety relies on the classification of the ships. The different classification societies have their own recommendations and guidelines on this subject, some are more detailed and developed than others. A few general observations from the societies' guidelines are:

- Most of the classification societies base the classification on a risk analysis or safety assessment. In some cases the items that should be included in the risk analysis are listed but very little advice is given on how the analysis should be conducted.
- Wording and terminology is in some cases different within the same document and it is in many cases not so easy to understand what is meant, this could be for instance the term battery enclosure/compartments, is this the battery itself or the room where the battery is placed. It is also not always clear if the documents use the same definitions as used for battery applications in general.
- When it comes to extinguishment the advice differs and can in some cases be different in different documents from the same society.
- In cases where reference is made to a specific standard, these standards are listed in section 5.4. However, usually little advice is given on how to test.
- There are also various levels where the requirements do not apply e.g. one class exempt battery installations less than 50 kWh, in general it is not clear how these limits have been set.
- Advice and regulations for other types of batteries is also limited.

Both Sweden and Norway have national rules where the Swedish rules are quite general in order to allow for innovation.

The Norwegian Sjøfartsdirektoratet has issued a circular V on safety on Li-ion propulsion batteries which contains a description of a thermal runaway propagation test as cited below.

“3.1. Propagation test 1

If the battery system design indicates that the below test set-up is not relevant, this should be clarified in advance with the NMA. A propagation test as described below should be carried out. Auxiliary systems which are integrated in the battery pack in order to prevent propagation and which are operative when the battery is in use, may also be used during the propagation test. Loss of these auxiliary systems should lead to shutdown of the battery system.

3.1.1. Test set-up

a. The test should be carried out in an enclosed space, as similar as possible to the manufacturer's recommendation for battery spaces. The temperature of the space should be equivalent to the maximum operating temperature (+/-5°C) for the battery system.

b. The tested module should be surrounded by other modules and be installed in a rack system similar to the one used onboard ships. The modules in the least favourable positions with regard to fire propagation from the tested module should be operative modules. The internal structure of the modules should not be changed. The remaining may be dummy modules as long as they have the same heat capacity, heat reflective properties and conductivity as the actual modules.

c. All operative modules in the test should have a 100% State of Charge at the start of the test.

d. The module being tested should be randomly selected from a production batch, and should not be altered apart from instrumentation. Any alterations made to cells in order to initiate the thermal event, should be clarified with the NMA in each case.

e. The cell or cell pair to be overloaded should have the least favourable position in the module with regard to propagation.

f. The safety functions of the battery management system (BMS) should be deactivated during testing.

g. The test should be instrumented to continuously record relevant data. Voltage and temperatures of the tested module and the other operative modules should be logged as a function of time. The temperature of the dummy modules should be logged in the same way. The temperature sensors should be placed on the surface closest to the module where the thermal event is initiated.

h. Modules in the test set-up should be continuously monitored and the result registered until the temperature is back to ambient temperature, and as a minimum for 24 hours after the thermal event occurred.

i. The test should be conducted without use of active external safety functions such as fire extinguishing system, ventilation, etc. in the test space.

3.1.2. A cell or cell pair in the test module should be overcharged with a voltage of at least 150% of the maximum charging voltage over time until a thermal event occurs. The charging current should be maximum of what the cell is designed for.

3.1.3. If a thermal event has not occurred after 4 hours, additional heat may be applied by using fitted heating elements.

3.1.4. For battery cells fitted with an internal circuit interrupt device (CID), where it is documented that this is functioning, the thermal event may be initiated by using heat.

3.1.5. Acceptance criteria Three witnessed tests should be carried out. The acceptance criterion is that no propagation occurs between modules. If the test fails, the test should be aborted, and the criterion of propagation test 1 has not been satisfied.

3.2. Propagation test 2

If propagation test 1 fails, the arrangement may be tested with active external safety systems upon acceptance from the NMA. The test set-up for propagation test 2 is the same as for propagation test 1, with the exception of item 3.1.1i which should be disregarded.

As for propagation test 1, three witnessed tests should be carried out. The acceptance criterion is the same: no propagation between modules. All tests should be successful.

When the battery system is fitted on board, active external safety systems should be installed, which should be equivalent to the test arrangement with regard to capacity and details. These systems should be available in all relevant emergency situations. If a gas fire extinguishing system is used to inhibit propagation, it should have capacity for at least two subsequent releases.”

This test description is the only one found that relates directly to batteries installed on board ships for propulsion. The requirement is that no propagation between battery modules should occur, a very important feature to test. However modules comes in different sizes and this requirement could be improved by requiring that this should be accompanied with a requirement that one has to prove the ability to manage a fire of a complete module sufficiently. The requirement that it should pass three tests is good as there is always variation between similar battery tests. The test is however challenging to perform and it could perhaps be difficult to find a test laboratory for it depending on size of the modules.

9 Potential mitigation means

9.1 Battery Management System

The BMS monitors and controls the battery system. The BMS has a multiple of sensors, e.g. each cell voltage, battery temperatures, pack voltage and pack current. The BMS typically also measure the electrical insulation between the battery and the outer (metal) chassis ground. In case of an insulation fault the BMS will shut down the battery. Figure 7 shows the principle of the current path for a Li-ion battery pack. The battery pack has a so called floating ground. In case of no isolation faults, there are no electrical connection between chassis ground and neither battery plus or battery minus. In large battery packs typically a multiple of fuses and contactors are used, and the cells are typically connected in several parallel electrical cell strings.

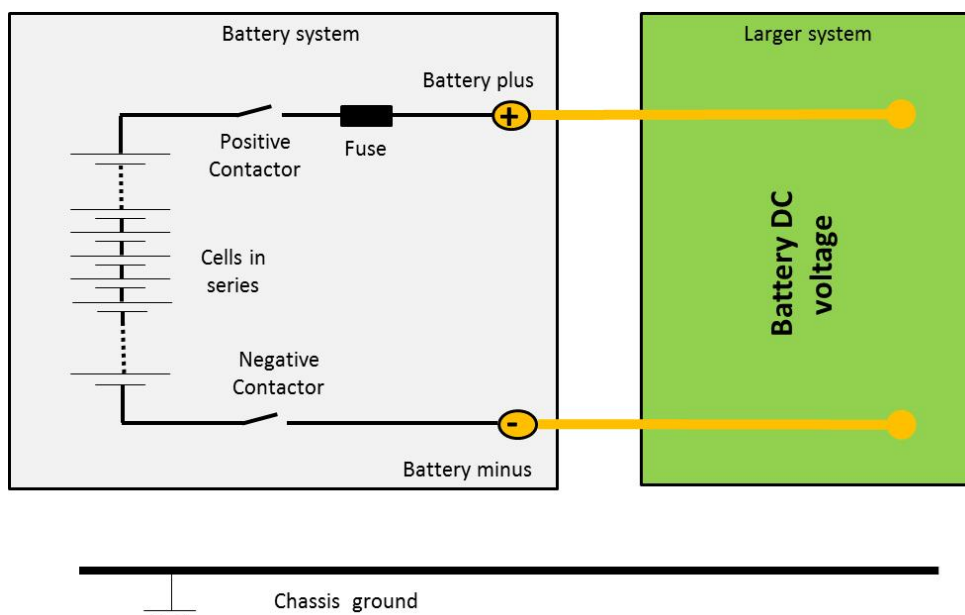


Figure 7 Schematic illustration of the current path of a battery system.

In case the BMS detect either a too low or too high battery temperature, it will take actions, e.g. increase cooling or heating, request a stop or lowering of the current from the surrounding system or simply shut down the battery (open contactors). Each cell voltage needs to be held within a range between an upper and a lower voltage limit. The limits vary with different Li-ion chemistries. In case any cell voltage is outside of this range, the BMS must shut down the battery in order to protect the cell, i.e. in order to keep it within the allowed cell voltage range. In case there is a too high current, either charge current or discharge current, the battery can handle it in several ways. The BMS can open the contactors which will stop the current. However, for large over-currents, e.g. short circuits, the contactors will typically not be able to open since they will be

welded by the large current, instead the fuse will be activated. There are different types of fuses, e.g. automatic fuses, melting fuses and explosion fuse.

A number of different abuse type situations can occur, see Figure 4. The BMS can protect the system from some of these situations, but not all. Table 3 gives a simplified general overview of cases when the BMS of Li-ion battery system can/cannot protect.

A single cell failure can potentially propagate to adjacent cells. The thermal management system can, at least for some situations, affect the heat spreading and its time development, e.g. stop or delay the cell-to-cell propagation.

Table 3 A simplified general overview of abuse situations where the BMS can/cannot protect the battery system.

Abuse type	BMS protection?	Protection strategy
External battery pack short circuit	YES	Disconnect the battery by using fuse or possibly contactors
External cell short circuit	POSSIBLE*	The BMS can protect if the short circuit current possible to interrupt by a circuit breaker.
Internal cell short circuit	NO**	-
Overcharge	YES***	Disconnect the battery by using contactors
Overdischarge	YES***	Disconnect the battery by using contactors
Mechanical cross / deformation / penetration	NO	-
External heating, mild	YES	Cooling by using Thermal management system
External heating, strong	NO	-

* This case refers to a situation with an external short circuit of one or multiple cells inside the battery pack. Theoretically, many short circuit paths are possible, and if the short circuit happens to be within a current path involving a fuse or possibly contactors then it is possible to stop the short circuit.

** Spontaneously starting on micrometre scale inside the cell battery due to e.g. particle contamination or dendrite formation.

*** The detection and the consequent actions until current shutdown must be rapid enough to ensure that the battery is not exposed to over/under voltages.

The BMS is a complex system of electronics and many sensors. A sensor fault or BMS fault can therefore happen, and appropriate measures need to be implemented to handle them. The voltage needs to be measured for each cell potential. The temperature is however typically not measured per cell; instead e.g. 1-2 temperature sensors are used per battery module (for e.g. 20 cells). The current of the battery system is typically measured at least on the battery outgoing connection. In order to handle sensor fault, additional sensors of all different types (voltage, current and temperature) are desired, in order for the BMS to be able to identify and evaluate faults. An example of how to detect a fault in the BMS is to compare the sum of all cell voltages in a module with the voltage value from an additional sensor that measure the battery module voltage.

The battery system and its control system, i.e. the BMS, can potentially involve different safety techniques and mechanisms. Presently, the BMS typically measures at least all cell voltages, the total battery voltage, the total battery current and the temperature at several locations in the battery system, within a certain time interval (e.g. 10 seconds). It is technically possible to increase the numbers of sensors, their measurement precision and the measuring frequency. However, this will add cost, weight, volume and complexity. Today the cost is the driver for decreasing the number of sensors. However, with more and better sensor data the overall possibilities for early detection and counteractions would increase.

Today there can for example be as few as two temperature sensors per battery module (about 20 cells) in some applications. The main purpose of them is typically to provide input to the thermal management system (cooling/heating) of the battery. Secondary they can be used for an indication of high temperatures in case of thermal events in the battery cells or current cabling or electronics, however early detection is typically not possible. So detection after an event has occurred is the general status of today's Li-ion battery systems. There are indications that some classification societies require one temperature sensor per cell which improves the situation considerably.

In case of a cell venting and releasing flammable and toxic battery gases, the detection of this event is typically only possible by cell voltage readings, however depending on cell type, venting is possible without change in cell voltage. In case the cell nearby the temperature sensor vents, the temperature sensor would indicate this event (if the temperature sensor is attached and placed onto the cell surface in such a way that it adequately represents the cell surface temperature). However if the cell is not located nearby the temperature sensor, the temperature sensor will not likely be able to detect the thermal event until the cell and possibly also the adjacent cells have been thermally fully involved during a significant time.

Electrochemical impedance spectroscopy (EIS) could be used in a battery system, however it will increase the cost. Different approaches are possible. For example, one relative simple measure is to use the cell voltage and current and use advanced data processing methods to determine the cell impedance, for one or a limited number of frequencies. A more complex approach would be to measure impedance of each cell for a spectrum of frequencies by using EIS installed in the battery pack, with appropriate electronics, e.g. individual cell on/off switches if needed by the method.

Today the BMS typically cannot detect gas release. For some cells, e.g. cylindrical or hard prismatic cells with a safety vent and current interrupter device (CID) installed, in case of proper function, the gas release occurs when the cell voltage drops (to 0 V), so if

the systems have these types of cells and the BMS detect 0 V a gas release might have happened, however, it can also be a sign of other events without gas release (for example a simple CID cell shutdown, without safety vent opened), or sensor cable coming loose, etc.

From abuse testing performed at RISE it has been shown that it is possible, at least for some situations (other not yet tested) that the cell can release gases without a change in cell voltage or temperature.

9.2 Gas and fire detection

9.2.1 Gas detection

In case of battery failure the batteries can generate and release gases before any fire event. Detection of these gases would possible enable an early response and could prevent a fire or explosion event as well as improve mitigation of any succeeding fires. Contingent actions include e.g. disconnection of the batteries, cooling of the batteries and increased ventilation.

The composition of the gases released from the batteries depends on the battery chemistry, however, it typically also depend on state of charge, temperature, pressure and surrounding atmosphere. Both toxic and flammable gases should be expected. Figure 8 shows an example of gas emissions from a Li-ion battery cell undergoing overcharge abuse. Emitted gases from Li-ion batteries are initially typically of white colours.



Figure 8 Gas release (venting) during overcharge abuse from a 30 Ah Li-ion battery cell with pouch prismatic packaging. Photograph: Fredrik Larsson.

It is important that a gas composition analysis is performed before configuration and installation of gas detectors, so that detectors can be adapted and optimized for the

expected composition of gases. Gas detectors are generally specified for either detection of toxic gases or detection of flammable gases. Flammable gases should be detected before the gas concentration has reached the lower limit of concentration needed for ignition of the gases and risk of an explosion to occur. Different gases and composition of gases means different concentration limits for flammability. Typically requirements specify detection at e.g. 20% of LEL (lower explosion limit). Venting of batteries will however release a large amount of gases in a short time, which means that the flammability/explosion limit can be reached almost immediately. In general, toxic gas detection needs more sensitive detectors since the levels of toxic gases that may be harmful for humans are often much lower than LEL of flammable gases.

Detection of flammable gases is most often associated with detection of different hydrocarbons. However, detection of hydrogen, carbon monoxide and carbon dioxide can also be useful as well as detection of other gases. There are different principles and technologies available for gas detection with different advantages and disadvantages. The conventional, simple and low cost catalytic sensor is often used. However, it requires frequent calibrations, surrounding oxygen and relatively high power. Another alternative is based on infrared, IR, technology. It is more robust and can be used in inert atmospheres, but to a higher initial cost. With IR it is also possible to use “open path” detection, which means that a transmitter and a receiver are positioned apart from each other and that detection is achieved along the whole distance in-between. Other technologies include semiconductors, electrochemical sensors, thermal conductivity sensors and absorbent filter tape.

Most technologies used for gas detection are associated with point detection. However, instead of using several separated point detectors, an alternative is to use an aspirating system, which means that air/gas is sampled from several positions to one sensor. The advantage is that one sensor can cover a larger area. However, if several sampling points are used there could either be a dilution problem, which means that the sensor needs to be much more sensitive than a corresponding sensor of a point detector, or there could be a delay time if the system alternate sampling from the different points, which means that monitoring of each point is non-continuous.

For a battery system it is possible to install one or multiple gas detection sensors inside the battery system to detect gas releases at an early stage. The gas sensor can be selected to detect hydrocarbons (e.g. the organic solvents used in the Li-ion battery electrolyte). One could also have a gas sensor that detects toxic gases, for example hydrogen fluoride.

If the gas detectors are not positioned close to safety vents or inside the battery pack the detectors must be positioned where the gases are expected to spread and accumulate. Important for placement of detectors is the air flow in the compartment, including re-circulating air, stagnant air and other flow patterns.

In case the gas release from the batteries is not ignited immediately it is expected that an explosive atmosphere can arise fast regardless of ventilation due to the large amount of gases that can be released. In that case some sort of explosion protection should be considered, including active detection and suppression as well as passive configurations, e.g. weak walls towards safe areas.

Since gas release in batteries is associated with temperature increase of the battery cell, early detection may also include temperature monitoring of the cells. This is normally included in the BMS and it is recommended to use many heat sensors, preferable one per cell. It is also important at which point on the outer wall of the cell the sensor is attached, since the temperature distribution on the cell surface can vary a lot. In order to use a thermal imaging camera for detection of cell failure the camera needs visually access to the cell surface. Today the battery module and packs are tightly packed inside metal cases so the thermal imaging camera cannot be a viable tool for detection of abnormal temperatures in the cells. However, in a large battery room a thermal imaging camera could be used to identify hot battery modules/packs but the use of temperature sensors is probably more reliable and less costly.

The most important question in case of cell failure and gas release is what actions that should be taken to avoid an explosion scenario or a propagating fire scenario. To answer that question it is also very important to know when the failure can be detected and if significant gas release in the battery room can be restricted.

9.2.2 Fire detection

Fires in battery spaces are expected to produce a lot of soot why conventional smoke detectors are considered to be sufficient. However, there are different types of smoke detectors available and also gas, heat and flame detection can be an alternative.

In general, combustion of a substance produces carbon dioxide, water, soot and heat and most solid based fuels are known to generously generate such fire signatures. Soot particles are a result of incomplete combustion and these particles are what make smoke black and the flames luminously yellow. From a detection point of view, soot is an easily recognizable phenomenon for automatic (and human) detection.

The smoke detector is generally claimed to give earlier detection than the heat detector, which is valid for many fuels producing much soot when burning, e.g. solids and petroleum based products and applies also to battery spaces. Smoke production is for these fuels namely high in comparison with the released heat at the early stages of a fire. Nevertheless, detecting heat could be a good alternative if the ceiling is low and the space is small, especially if the fire starts as a gas fire due to battery venting since that fire would result in relatively high temperatures in the enclosure. However, in that case flame detection would be the fastest one.

Generally, using gas detectors for fire detection can give very early warning in case of smouldering fires and can also be combined with the gas detection system used to detect gas leakage (before fire). For example, carbon dioxide can be monitored to detect both a gas leakage and a fire. One can also use the same sampling system, but having different gas sensors.

If CCTV cameras are used for surveillance, these can also be used for fire detection. Image analysis software is used to identify possible fires and give an alarm. One benefit of such systems is that the extent and position of the fire is easily monitored in case of an alarm at the early stages of a fire.

9.3 Fire extinguishment

The key to fire extinguishment and mitigation of progressing thermal runaway is to cool the cells and thus water is preferred, due to its high cooling capabilities compared to gaseous extinguishing agents and also that it can reach the cells easier than e.g. powder. Also being able to introduce the water into the actual modules would be beneficial as this would provide improved cooling of the cells. It is however important not to introduce it by cutting or similar activities. There might be a risk for short circuit when water is introduced. There are currently limited investigations available on the potential for fresh or sea (salt) water to cause short circuits in batteries, however salt water increases the risk for short circuit. Water should only be applied if there is a thermal runaway taking place, as the possibility for short-circuit at that stage is of less concern. Additionally, if the modules are designed so that thermal runaway in one cell does not cause a thermal runaway in a neighbouring cell by means of distances between cells or thermal insulation, then there is less need for applying water into the modules. There are also fire-fighting systems available that utilises foam instead of water within the modules.

When considering the fire extinguishing media, it is important to remember that it is not insulation of the cells that one would like to achieve but cooling the cells. If the cells are insulated from the ambient the situation might be worsened as the heat from the thermal runaway needs to stay within the cells and cannot be cooled away. It is also important to consider that flame extinguishment would potentially also worsen the situation as venting cells without any flame can potentially result in a flammable gas mixture build-up that can be ignited and cause an explosion.

Besides the battery cells, it is important to consider fires from other materials within the battery system, e.g. plastic part, thermal isolation, cables, electronics, BMS, and electric component (e.g. contactors). A fire in these parts of the battery system can be considered a more “traditional” fire originating from e.g. overheating in electronics or electrical cable connectors. Since that can be the source of a battery system fire, fire-fighting of those non-cell parts can be essential.

It is also important to remember that the probability for a thermal runaway is usually limited due to other safety systems such as BMS, CID and careful construction of the cells. However, there is always a risk for external heating be it due to a fire within the actual room or an adjacent room. Extinguishing systems for taking care of such fires are thus also very important in order to protect the batteries.

9.4 Other means

Careful design of the modules and cells are key actions for the safety of any battery propulsion system. As there is less constraints on weight and volume onboard large ships compared to for example a car it would be possible to separate the cells better. Such a measure could prevent or minimize propagation from cell to cell of a thermal runaway. If it is not possible to prevent cell to cell propagation perhaps it is possible to

prevent module to module spread or to have separated small packages of cells within a module.

Careful design of the control system such as BMS and the operational range is crucial and so is the quality of cells. The BMS is also an important component in getting an early indication that something is going in the wrong direction so that measures can be activated in time to prevent further heating such as electrically shutting-down the battery or increased cooling or possible activation of an extinguishing system. It is also beneficial to try to release possible venting gases from the battery to the outside of the ship or to areas where they cannot do any harm as required in Circular V from the Norwegian Administration Sjøfartsdirektoratet.

9.4.1 Compartmentation and ventilation

In order to mitigate the consequences of a possible explosion, explosion vents are possible safety measures. It may however not be so easy to design explosion vents for a ship, as they usually have complex geometries that create turbulence and therefore the pressure increase rate would be difficult to predict in an accurate manner. Furthermore, a common explosion venting strategy is in principle to have three strong walls and one weak wall, which can be difficult to apply to a ship. Another aspect that influences a potential explosion is that many spaces on board ships are filled with equipment. It could be expected that battery rooms will be densely filled with batteries and will contain as little free space as practicable.

10 Test methods

10.1 Detection

IMO issues numerous of circulars, which the FSS Code or any other Code of higher hierarchy may refer to regarding guidelines or testing in specific situations. There are at least two circulars that cover fire or gas detection:

- MSC.1/Circ.1035 – Guidelines for the use and installation of detectors equivalent to smoke detectors
- MSC.1/Circ.1370 – Guidelines for the design, construction and testing of fixed hydrocarbon gas detection systems

Circular 1035 basically just states that the requirements in the FSS Code apply and that the detector should be equivalent to smoke detectors required by SOLAS. EN 54-7 is mentioned as an example of required level of testing.

Circular 1370 are a little more detailed, but the requirements are functional. There are not many prescriptive formulations, with clear levels of what is accepted. Focus lies on what to consider and which type and configuration of detector to use. There are also some chapters about system control, maintenance, calibration, and operating instructions, which are a little more precise.

EN 54 is a European standard focused on product approvals rather than application considerations. This makes it quite general, however, it is clearly stated that the standard is only valid for fire detection in buildings, but that it could be used as guidance for other applications. EN 54 specifies requirements, test methods and performance criteria for fire detection and fire alarm systems. The EN 54 standard contains several chapters with their own releases where each chapter covers a specific component (with a few exceptions) in the fire alarm system. For example, there are different chapters for power supply equipment, indicating equipment, short circuit isolators, radio links, etc. and then different chapters for heat detectors, smoke detectors, flame detectors and so on.

ISO 7240 is the international counterpart to EN 54 and in many parts they are almost identical. The structure, content and test procedure in these standards are very similar, but they are not identical since there are different workgroups preparing ISO 7240 and EN 54.

Factory Mutual Insurance Company or, as the communicative name is, FM Global, have over 200 of their own approval standards and the standards covering different types of fire detection are:

- FM 3210 Heat detectors for automatic fire alarm signalling.
- FM 3230 Smoke actuated detectors for automatic fire alarm signalling.
- FM 3232 Video image fire smoke detectors for automatic fire alarm signalling.
- FM 3260 Radiant energy-sensing fire detectors for automatic fire alarm signalling.

These standards are focused on product approval and the main content consists of a test program with performance requirements, similar to EN 54.

Underwriters Laboratories Inc. (UL) has about 1500 published standards for safety. Some of these standards concern fire safety and the main ones about fire detection are:

- UL 217: Standard for single and multiple station smoke alarms.
- UL 268: Smoke detectors for fire alarm systems.
- UL 268A: Standard for smoke detectors for duct application.
- UL 521: Standard for heat detectors for fire protective signalling systems.
- UL 539: Standard for single and multiple station heat alarms.
- UL 2034: Standard for single and multiple station carbon monoxide alarms.

Station alarm means one or several units that works alone, compared to alarm systems where several detectors, sounders, etc. is connected to a control unit. These UL standards have the same structure as the FM and EN standards mentioned above with main focus on the approval test program.

It is considered by classification rules that battery spaces shall be monitored by conventional smoke detection. These detectors should be approved according to a suitable product approval standard in addition to onboard testing, specified in the FSS-code. Onboard testing should verify the efficiency of the system under varying conditions of ventilation and with smoke release in different positions of high fire risk.

Gas detection system designed to detect a specific substance should also be approved by a suitable standard to verify the application. According to the regulations, a simulation or test for each specific case is needed to come up with good positions. Not only the airflow is important but also density of the gas composition. There is probably a need for verifying tests. It should also be tested such that a failure in the gas detection system does not result in disconnection of the batteries or other alarm response actions to occur.

10.2 Fire-fighting

There are currently no extinguishing test methods specifically designed for battery systems and there are no test methods that capture the specific issues with battery systems. It is advisable that realistic test methods, with appropriate acceptance criteria, for fire-fighting systems are developed.

The methods need probably be different depending on what type of system and/or agent that is to be employed, whether the system is integrated with the battery system or if the system is installed in the battery room. There is currently no outline available for this type of testing. Ad hoc testing has probably been conducted in many cases, but publicly available information on the test set-ups and evaluation of the test method used is very limited.

10.3 Other means

Preventing propagation of a thermal event in a battery from one cell to another or from one module to another or part of module to another part is the key to safety. The only test available on this is the propagation test in IEC 62619 and circular V from the Norwegian Flag State Sjøfartsdirektoratet.

In IEC 62619 a thermal runaway is initiated in a cell by means of heating, overcharge, nail penetration, a combination of the methods or other method. As the test is a propagation test and not a cell test, internal circuit is not included as an option, i.e. the thermal runaway is a trigger in the test. The module is observed for one hour after the thermal runaway occurred and the criteria is that no external fire or battery case rupture should occur. This requirement is not very well defined and leaves room for interpretations. Also one hour observation time could be too short in some cases. It was also noted that the no consideration is given to the heat transferred to the surroundings in the criteria, which makes them incomplete. The amount of transferred heat can be significant for large battery packaging. It would be better to have a test that actually evaluated the potential for fire spread between cells or battery modules, by for example temperature measurements on adjacent cells. The propagation test as described in circular V evaluates the risk for fire spread between modules and evaluates this in an appropriate manner as we see it.

11 Suggestions for continued work

Summarizing the approval process, it is up to the ship designer (ship owner) to undertake a safety assessment of the batteries and the battery installation. This should include all potential hazards posed by the batteries and all potential hazards threatening the batteries. This assessment is partially based on a safety description made by the battery manufacturer for the specific type of battery that is intended to be used. It is required that fulfilment of applicable regulations is addressed and also that an additional assessment is made evaluating if the requirements are appropriate for the battery type installed.

This means that a lot of responsibility is imposed on the ship designer that has to rely on the battery manufacturer for the safety assessment. To cover all the risks when designing for battery propulsion is a difficult task. It is difficult for a ship designer to cover the wide range of knowledge necessary, in particular as battery development is fast and safety aspects are not always communicated, or perhaps even not known.

A workshop held in Gothenburg on June 14, 2017 gathering different stakeholders from Sweden, Norway and Finland identified fire safety as the main challenge for the introduction of battery propulsion at sea. During the discussions, several questions/concerns were raised. These could be divided into four areas: general design of the ship and the battery system, details related to risks and safety measures, type approval and tests, and information and knowledge for safe use in the application.

11.1 General design process of the ship and the battery system

One major obstacle for the ship yards and ship designers is the lack of predictability during the design process. It is difficult to predict the outcome of the risk assessment since this is not performed until after the contract has been signed. This makes it very difficult to calculate the costs of the battery installation, costs of the required fire-fighting system, costs of the required fire integrity of the battery spaces and other costs. This could lead to higher costs since ship yards, aware of the possible costs, needs to increase their estimated price to cover these unknown (at the time of the offer) costs. There is also a risk that designers or yards new in the area underestimates the costs which could lead to economic difficulties and give incentives to cut corners.

There were also questions raised about the risk assessment process which was expected to be time consuming and costly. Guidance about acceptance criteria and scope as well as required level of detail of the assessment were asked for. It is difficult to determine both the level of safety of the existing fleet as well as the level of safety of a ship with a battery installation, especially since there are no reliable statistics about the risks from batteries, for example the frequency of thermal runaway.

It was proposed that the risk assessment should be conducted earlier in the process, before tenders are asked for. Or, alternatively, that batteries or the battery system shall be type approved together with necessary safety measures.

Some participants expressed that it is difficult to know who is responsible for what. What should be done by the manufacturer, the supplier, the designer, the administration, the class society, and finally the crew? The responsibility is sometime shared or even unclear.

11.2 Details about risks and safety measures

The next area of concern is that more detailed knowledge about different battery technologies could be difficult to obtain especially since the development is relatively fast. It was concluded that it takes time to keep the knowledge updated. One concern is about choosing appropriate fire-fighting systems for different battery chemistries. Battery manufacturers often recommend several completely different systems, for example both water mist and gaseous systems. In the risk assessment, it is required that the suitability of the fire-fighting system with regards to the specific battery technology is analysed.

In a battery failure, gas and smoke may be released and the possible composition of these gases is often unknown. It has been shown in experiments that they may be very toxic, e.g. contain dangerous amounts of HF. Guidance on how to deal with the gases and the possible hazards of releasing them outside the ship was asked for. The same questions were raised about ventilation of the battery storage space in case of a thermal runaway. The advice from the researchers was that ventilation is very helpful but it is difficult to give general recommendations about the required number of air changes.

The best location of batteries and battery spaces were discussed and another question brought up was related to the fire integrity of the battery space. In most class rules A-0 is required. However, in order to protect the batteries from fires in adjacent compartments it could be advisable to increase the insulation to A-60.

There were also concerns about the details of the BMS systems. Sometimes it is the battery manufacturer that makes the BMS but it could also be a separate supplier. Questions such as at which level shall a charge be regarded as an overcharge, needs to be addressed. Other crucial events and the response of the BMS also need to be defined. For example, there are in some cases requirements that at least 50 % of the battery capacity shall always be available. And the ship master could also need to override the BMS if it is required for the general safety of the ship. Loss of power in an emergency event may be worse than destroyed batteries.

11.3 Type approval and tests

There was a strong wish for having type approved batteries and that the battery system should be approved as a complete system. This should include the batteries, the accepted fire-fighting system, the required fire integrity, ventilation of the space, EX classed equipment, the BMS and procedures during use. If this could be achieved it would considerably facilitate the introduction and use of batteries.

Generally accepted type approval tests of batteries need to be developed. It is essential that the tests are developed for the purpose of safety when used on board ships as the

tests available today in general are not very well developed and proper acceptance criteria are missing. In addition it is important to know what one is designing for, e.g. in terms of fire-fighting system: is it cooling of the cells, knock down of flames or what is the safety strategy? The tests required in the Norwegian circular was considered hard by some but since they are applicable to all batteries they seemed to be fair. Other participants at the workshop thought that these tests were good and necessary.

Regarding tests of fire-fighting systems, it was expressed that it would be good if the system could be tested with a standard battery. It is very costly to test how the system performs against each brand of batteries.

11.4 Information and knowledge of the use

The maritime authorities in both Norway and Sweden requires that the ship owner develops a clear strategy for the safety of the battery system. During the workshop, it was expressed that there is a lack of knowledge and information about this, especially the battery safety and the use on board the ships. Questions were raised on how the BMS works, when should or could the Captain override the system, what to do in case of an emergency, daily care and use on board ships. For small vessels, totally automated battery installations were asked for.

Several participants raised the training is important, including a strategy on when to shut down the battery system and when not.

On existing smaller ships one strategy is to try to confine a fire to the battery space as long as possible, to provide time for abandoning the ship in the case of a fire. Flooding of the battery space is also a strategy mentioned. Another strategy that was discussed is the possibility to dump the batteries overboard (with later retrieval). However, little information on these strategies is available so far and further elaboration is necessary before their suitability can be assessed.

11.5 Conclusions about future work

Many of the participants at the workshop had urgent problems that needed to be solved, since they were in the process of designing ships with battery installations. It was concluded that these problems have to be addressed by the designers together with the classification societies and the Administrations. In the long term, generally increased knowledge and development of publicly available strategies, training and designs would be useful.

Most Administrations requires that the ship owner develops a clear strategy for the safety of the battery system. This includes the fire-fighting systems, the design of the battery spaces, ventilation and emergency procedures.

As part of the workshop the participants could vote on six different areas which was of most importance to them, the results of this vote was:

Area 1: “Guidance”

- Guidance of preventive measures.
- Guidance of appropriate gas and fire detection systems for different battery chemistries.
- Guidance of appropriate suppression/extinguishing systems for different battery chemistries.
- Guidance of appropriate battery spaces/enclosures for different battery chemistries.
- Guidance of appropriate approval tests for different battery chemistries.
- Guidance on safety strategies.

“Guidance” received 29% of the votes which emphasizes its importance.

Area 2: “Simplifications of the process” received 2% of the votes.

Area 3: “Fire fighting”

- Establishment of performance objectives for fixed fire-fighting systems
- The development of appropriate fire test methods for approval testing of fire fighting systems and other measures
- Research on fire fighting systems integrated with the battery systems
- Investigation of potential new water additives

“Fire fighting” received 21 % of the votes, underlying its importance.

Area 4: “Safety strategies - An overall view of passive and active fire protection measures”, including but not limited to:

- The performance objectives.
- The BMS system.
- Design of the cells, modules and the battery packs.
- Gas and fire detection.
- Selection and design of the fire-fighting system.
- Ventilation approach.
- Explosion protection measures.
- Means for manual fire-fighting.

“Safety strategies” received 17% of the votes

Area 5: “Preventive measures, knowledge and training”

Preventive measures, knowledge and training received 17% of the votes.

Area 6: “Safety assessments”

- Guidance on safety assessments.
- More detailed safety descriptions (e.g. include more of what normally is covered by the safety assessment).
- Creating a knowledge database? What type of installations has been approved? What types of extinguishing for different battery chemistries?

“Safety Assessment” received 13% of the votes.

From the different categories it seemed that the knowledge database point in Area 6 was easy to arrange as e.g. the Norwegian Flag (Sjøfartsdirektoratet) said their data on the approved systems is available. However, one drawback with looking at systems that have been approved is that these approvals are based on old and potentially outdated knowledge and experience and previously approved systems might not be approved today when more risks have been identified. There are also uncertainties whether all data is available in all cases or if data is considered as confidential and how easy it is to obtain access to the data. A database made available by the authorities would perhaps still improve the situation.

For fire fighting/extinguishing measures one project will start this year (2017) financed by Sjøfartsverket where RISE will conduct fire suppression tests demonstrating the performance of different typical fire-fighting systems and agents against Li-ion cells mounted in a battery pack mock-up. The test results and test set-up will be made public in order to meet the need for information in this area. This is important as there are many different recommendations appearing, but it is often unknown what the basis is for these recommendations.

No immediate other potential project was suggested during the workshop, except that it was concluded that there is a huge need for more knowledge about Li-ion batteries, their risks and potential mitigating measures.

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