Maritime & Coastguard Agency

MARINE GUIDANCE NOTE

MGN 550 (M+F)

Electrical Installations - Guidance for Safe Design, Installation and Operation of Lithium-ion Batteries

Notice to all Shipowners, Ship Operators, Masters and Officers of Ships, Ship Designers and Shipbuilders of Vessels fitted with or intended to be fitted with Lithium-ion Batteries

This notice should be read alongside the machinery and electrical provisions within UK ship construction regulations inclusive of UK codes of practice and statutory instruments.

Summary

The intent of this Marine Guidance Note is to provide the marine industry with best practice guidance to facilitate safe and environmentally-friendly lithium-ion battery solutions for vessels utilising lithium-ion batteries as part of a hybrid power system or as the sole source of propulsion power. Topics include: battery system design, storage & transportation, installation, operations & procedures, maintenance and disassembly/recycling.

1. Introduction

1.1 In recent years the use of lithium-ion batteries in the marine industry has risen mainly due to improvements in technology and the economic or legal drivers which require the cutting of fuel costs and exhaust emissions. Lithium-ion and other battery technologies have become viable energy storage options due to their high energy density and capacity for high charge/discharge rates which allow them to be used for hotel or auxiliary loads and low power applications (e.g. low speed propulsion). For example, in a hybrid power system the incorporation of a lithium-ion energy storage system may permit the engines to be shut-down for periods of low energy usage, e.g. when a tug is on-station or when a motor-yacht is travelling at low speeds; this can increase the overall fuel efficiency of a vessel, it can reduce the engine maintenance costs and cut exhaust emissions, it can also reduce noise levels and vibrations. However, the high energy densities and the alternative materials within these batteries pose their own risks which need to be carefully considered before these batteries are incorporated into a marine structure.

1.2 This guidance has been developed via formal consultations with the UK marine industry to identify industry best practice, however it is understood that this guidance will not cover every eventuality in design, installation, operation, etc, and each case should be considered separately. There are several areas within a design where the use of risk assessments or hazard identification techniques (such as Failure Modes Effects Analysis (FMEA)) should be performed to understand the potential safety issues for personnel, the environment, the vessel and the vessel's operations.

1.3 This guidance does not supersede any other guidance or statutory instruction and should be taken into account when developing designs for lithium-ion battery power systems. This guidance does not replace the need for sound engineering practice nor seamanlike precautions.

2. Contents

3. Definitions

3.1 A *cell* is a single electrochemical unit in its simplest form, typically packaged in:
metal cylinders; or
flat, rectangular metal or plastic cases ("prismatic cells"); or
heat-sealed foil pouches

3.2 *Cell drift* is when two or more cells are in a state of energy imbalance. If not corrected (by a battery management system), excessive cell drift can lead to over-charging or over-discharging of cells and can in-turn lead to defective cells or a potential safety hazard.

3.3 A *battery* is an assembly of two or more cells that are electrically connected together and fitted in a case with devices as terminals, markings and protective devices that it needs to function properly and safely.

3.4 A *lithium-ion battery (secondary)* is rechargeable and utilises the transfer of lithium-ions between the electrodes. Lithium-ion batteries do not contain metallic (elemental) lithium and include the following sub-categories: lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NCM), lithium cobalt oxide (LCO), lithium nickel cobalt aluminium oxide (NCA), lithium titanate oxide (LTO), lithium manganese oxide (LMO), and others. Such batteries are used in mobile phones, laptop computers, electric vehicles and large energy storage installations.

3.5 A *lithium metal battery (primary)* is usually non-rechargeable, contains metallic lithium and features a higher energy density than most other non-rechargeable batteries. Lithium metal batteries are often used in calculators, pacemakers, remote car locks and watches. **Lithium metal batteries (primary) are not considered within this guidance.**

3.6 *Thermal runaway* is when a cell enters a self-heating state (exothermic reaction) where the heat generated is greater than the heat dissipated. (Note: thermal runaway can begin at temperatures as low as 120°C depending on the cell size, design and chemistry, and from the initiation of thermal runaway, a cell's temperature can rise to a maximum in under 2 minutes.)

3.7 A *separator* is a material between the anode and cathode which has pores that close to prevent ion transfer and electrical activity if the temperature goes above a specific level (approx. 130°C to 150°C). If heating continues then these separators usually fail resulting in a generalised short circuit.

3.8 A *protective device* include equipment such as fuses, diodes or other electric or electronic current limiters designed to interrupt current flow, block the current flow in one direction or limit the current in an electrical circuit. Two examples which can be fitted at a cell level are the *current-interrupt device (CID)* which may break a cell's circuit upon failure and a *positive temperature coefficient (PTC) device* which can limit or stop an electric current dependent upon its temperature. Fuses or circuit breakers are commonly fitted at a system level and act to break the circuit when certain parameters are reached (e.g. excessive current).

3.9 *State of charge* is the available capacity in a battery expressed as a percentage of rated capacity

3.10 *State of health* reflects the general condition of a battery and its ability to deliver the specified performance compared with a new battery.

3.11 A *battery management system (BMS)* is an electronic device that controls, manages, detects or calculates electric and thermal functions of the battery system and provides communication between the battery system and upper level control systems.

4. General Overview

4.1 The contents of this guidance will not cover every eventuality in design, installation, operation, etc, and each case should be considered separately. The use of risk assessments or hazard identification techniques should be performed to understand the potential safety issues for personnel, the environment, the vessel and the vessel's operations caused by the incorporation of a lithium-ion battery. Suitable mitigations or safeguards should be implemented to reduce risks to an acceptable level. In general, amendments to operational methods or procedures should not be accepted as an alternative to the safe design of a battery system and its installation in a vessel, whether this be regarding location, materials, equipment, auxiliaries, construction method, etc.

4.2 The design of a battery system within a vessel should anticipate future changes. These changes might relate to the operational tasking of the vessel, modifications to the electrical equipment, upgrades to the battery cell chemistry (and energy density) or caused by obsolescence of equipment. It should be highlighted that any modification which changes the requirements upon an existing battery system should be thoroughly assessed against the original requirements of the battery and its current state of health.

4.3 Table 1 details a few common cell chemistries which are used in the marine industry. **Please note that this guidance notice has been written primarily for lithium-ion batteries.**

Table 1: Common cell chemistries used in marine battery systems

Cell Type	Cell Name	Advantages	Disadvantages	Failure Mechanisms
Aqueous (Lead-Acid)	Lead-acid	Low Cost	Low energy density	Short circuit, loss of electrolyte
Aqueous (Alkaline)	Nickel cadmium	Durable, good low-temperature performance	Low energy density	Gas barrier failure, short circuit, loss of electrolyte
	Nickel-metal hydride	High energy density	Poor charge retention	Thermal imbalance
	Nickel-zinc	Low cost	Low energy density	Zincate deposits on nickel electrode
	Silver-oxide	High energy density, low self-discharge	High cost, poor performance at low temperatures, poor lifecycle	Shape change and dendrites
Non-aqueous	Lithium-ion	High energy density, low self-discharge	Cannot withstand overcharge, degrade when over-charged, safety concerns	Under-over-voltage, thermal runaway

5. Hazards of Lithium-ion Batteries

5.1 Lithium-ion batteries can be a powerful, reliable and safe technology for the marine industry however this technology also brings a different set of hazards caused by dissimilarities with conventional battery technologies such as lead-acid. These additional hazards are discussed in the sub-paragraphs below to raise the awareness of designers, shipyards, crew, and any other persons who are introducing lithium-ion batteries. The remainder of this MGN addresses these hazards through considerations for the safe design of a lithium-ion battery and its employment within a vessel. It should be noted that many of these considerations may also be relevant for conventional battery technologies however these have been included for completeness and to highlight the totality of risks posed to personnel, the vessel, the environment and the vessel's operations.

5.1.1 Physical damage to lithium-ion cells, such as puncturing, crushing or mechanical shock, can cause cell defects, electrolyte leakages or local short-circuits within the cell. The electrolyte contained within lithium-ion cells can cause severe irritation to the respiratory tract, eyes and skin and some cell chemistries and designs may emit hazardous gases which are both toxic and flammable. Cell defects or local short circuits can create a localised heat source which could result in temperature increases within a cell and a possibility for thermal runaway.

5.1.2 An inadvertent increase in cell temperature can be considered the most significant risk to the integrity of a lithium-ion battery installation. Temperature increases within a cell can cause the break-down of internal components which can lead to local short circuits, venting of materials from the cell and further temperature increases. If these temperature increases become uncontrolled it is known as thermal runaway and it is likely that this may cause a chain reaction in adjacent cells/batteries. **A key hazard of lithium-ion technology is the way a minor lithium-ion cell defect can quickly cascade into a full battery fire incident.**

5.1.3 A large increase in cell temperature can cause violent venting of gases or chemicals which could create a hazardous environment of air contaminants, with corrosive or flammable vapours leading to a fire or explosion. Lithium-ion batteries may produce hydrogen gas, carbon monoxide, carbon dioxide, halogens and methane, among others. Under failed conditions, lithium-ion batteries could produce temperature increases over 1000°C.

5.1.4 Lithium-ion cells can store significant quantities of potential energy and a fire incident can develop very quickly, therefore the fighting of a lithium-ion fire requires thorough attention in design and on board procedures. The hazards associated with a lithium-ion fire emphasise that it may not be feasible to access a battery compartment during a fire and therefore structural fire protection and fixed fire suppression systems may be relied upon. In addition, following a lithium-ion battery fire, there may be toxic and harmful combustion by-products and contaminated used fire suppression medium.

6. Cell and Battery Handling Procedures

6.1 Appropriate personal protective equipment should be worn at all times. When applicable, safety management procedures (such as Permit To Work) should be enforced prior to working on batteries. Such procedures assist with the control of a space and aid the checking of hazardous factors (e.g. checking for a gas-free environment).

6.2 Work surfaces which are likely to be used with regards a battery installation or maintenance are to be insulated such that the risk of short circuit is minimised. Work surfaces should be clean and free of sharp objects that could puncture a cell.

6.3 Lithium-ion batteries should be safely handled and this includes: never throwing batteries in a fire or expose to high temperatures, not soaking batteries in water or seawater, not exposing batteries to strong oxidisers, not exposing batteries to mechanical shock and never disassembling, modifying or deforming batteries.

6.4 When storing or transporting lithium-ion batteries by air, sea, road & rail, batteries will need to have completed UN Transportation Testing (UN DOT 38.3) which includes tests for altitude simulation, thermal variations, vibration, shock, short circuits, impact, overcharge and forced discharge. For transportation, lithium-ion batteries also come under UN Dangerous Goods classification 9 'Miscellaneous Dangerous Goods' and it is the person or business shipping the goods who is responsible for classifying, marking and packaging the dangerous goods. In the UK, the Department for Transport provides guidance for compliance with the transportation regulations for air, sea, rail, road, etc; (see www.gov.uk for more information). In addition, consideration should be given to the following:

6.4.1 Damaged cells/batteries require special precautions to be taken prior to transportation.

6.4.2 When in storage, cells should be stored as per manufacturer's instructions – this is likely to require: the protection of live terminals, a well ventilated area with low humidity and out of direct sunlight, and a consistent ambient temperature as many cells experience a longer shelf life when kept cool.

6.4.3 Cells should be stored in an isolated area away from combustible materials or dangerous goods. Depleted cells should be stored separately.

6.4.4 Care should be taken to ensure that heavy items to not crush or puncture the cell cases.

6.4.5 All risks to the cells, the storage area and other stored goods should be considered prior to storage.

6.4.6 The number of cells stored in any storage area should be monitored and limited as necessary.

7. Construction of a Battery

7.1 Cells, batteries and supporting systems can be combined in many different ways and it is important that the system is designed and constructed using a detailed understanding of how these elements interact. It is strongly recommended that batteries are built by the cell manufacturer or by a manufacturer with a detailed knowledge of the cell chemical properties and the overarching requirements of the battery. Modifications to a cell, battery or power management systems should always be in accordance with the manufacturer's recommendations.

7.2 It is recommended that all cells are tested in accordance with UN Transportation Testing (see paragraph 6.4). It is also recommended to obtain the cell manufacturers Material Safety Data Sheet and/or cell Technical Specification which may detail: maximum charge/discharge currents, maximum state of discharge, temperature limits for separators or current intercept devices (CID), acceptable values of cell drift, etc.

7.3 The chemistry of lithium-ion cells can vary considerably between manufacturers and may even vary between production runs from a single manufacturer. Batteries can only safely operate within the operating limitations of the lowest common denominator of the cells and hence it should be ensured that the selected cells (and any replacements or spares) have compatible cell chemistries if mixed within one battery. For example, for cells arranged in series, the lowest-capacity cell will determine the battery discharge time and the highest-capacity cell will determine the battery charge time. It should be noted that lithium-ion cells age over time even if they are unused.

7.4 To ensure the safe operation of a battery and to prevent cascading events leading to a major incident, in general, the design of battery systems should include mitigations prioritised at the lowest cell design level. Therefore, although temperature monitoring might be incorporated at any level (e.g. cell, battery, battery management system or within the compartment of the vessel), temperature monitoring should be prioritised at the cell level, rather than within the compartment, for the earliest identification of a defect and the best possibility of avoiding an incident.

7.5 Battery manufacturers should ensure that batteries are designed with due consideration to safe design. As an example, the construction of the battery should have an appropriate ingress protection rating (see IEC 60529 - Specification for classification of degrees of protection provided by enclosures) and be constructed of appropriate materials as determined by the risk assessment method detailed in paragraph 4.1. Further considerations may be required to: ensure adequate heat dissipation, permit cell monitoring, permit prompt fire detection and fire fighting, ensure cells are restrained during vessel motions (including emergency scenarios), provide the cells physical protection, etc.

8. Battery Management System

8.1 The battery management system is required to maintain the condition of the cells and battery and protect them from unsafe situations such as internal battery defects, excessive external demands (e.g. a high current demand) and overcharging. It must be ensured that the battery management system is compatible with the requirements of the battery system, the other battery components and the vessels electrical equipment. The use of risk assessment methods are important to ensure that all of the potential failures in the battery (and in the vessel, see paragraph 9.2) have been appropriately considered with mitigations adopted according to the severity of risk.

8.2 Temperature monitoring can be considered the first warning for the thermal degradation of lithium-ion cells and should be continuously monitored with out of tolerance readings causing automatic responses within the battery (e.g. shut-down of a group of cells). It is recommended that temperature monitoring is provided at the cell level, especially if the batteries experience high charge or discharge rates. The battery management system may actively manage battery operations with respect to the temperature of the battery to improve efficiencies and to further reduce the risk of high temperature incidents. Due to the importance of temperature on lithium-ion batteries, continuous temperature monitoring may also be linked to responses external to the battery (e.g. isolation of the battery, early warning alarms and fixed fire suppression systems).

8.3 The battery management system should limit currents to ensure the battery remains in a safe condition. Permitted currents may be controlled relative to the state of charge and should take account of the battery's state of health through-life.

8.4 Lithium-ion cells, unlike other conventional battery technologies, should not be charged in excess of 100% state of charge as this may cause rapid failure of the electrodes and possible thermal runaway. Discharging below the minimum safe voltage can also cause cell damage. Unlike other battery technologies, it is therefore not possible to balance the state of charge of several lithium-ion cells using top-off or trickle charging of the battery, and it is vital that charging is stopped immediately if there is an unacceptable temperature rise - battery management systems should only be employed if they are compatible with lithium-ion batteries and are suitable for the application.

8.5 The battery management system should be capable of monitoring cell voltages and currents to a high resolution in order to ensure that the voltage of each cell remains within the range specified by the manufacturer. Cell voltages should be continuously monitored with an automatic alarm if these voltages exceed or fall below set limits, and a cell or battery shutdown should occur automatically if any voltage approaches the cell-damage threshold.

9. Battery Installation in a Vessel

9.1 This section provides guidance to ensure that the hazards associated with installing and operating a lithium-ion battery on a vessel do not lead to unacceptable risks to persons, the vessel, the environment, or the vessel's operations. For vessels to which the SOLAS Convention applies, *SOLAS II-2 Part D Electrical Installations* will take precedence over the following paragraphs however their content should be considered.

9.2 The role of the battery should be clearly defined for its intended use in a vessel; for example, the battery may be a small part of a hybrid system, or it may be the sole source of propulsive power. A risk assessment method such as an FMEA should be performed to assess the effects of a battery system failure upon the vessel and its operations. These assessments should consider the vessel's different operating modes and the state of health of the battery through its intended design life.

9.3 The vessel should employ its own electrical protective devices (e.g. fuses or circuit breakers) to protect the battery and personnel but also to prevent damage to ships equipment caused by battery defects. A positive lockable means of isolating the battery should be provided to allow maintenance.

9.4 The location of the battery compartment should take into account the operational role of the battery (e.g. whether the battery is used for emergency power during an engine room fire) as well as the effects that a battery fire would have on the vessel. Consideration should be given for avoiding adjacent compartments containing sources of heat or significant fire loads as increases in battery compartment temperature could affect battery operations or lead to thermal runaway. It is expected that further considerations would be necessary for vessel not built of steel or equivalent material. A full assessment should be made for the routing of cables and pipework through the battery compartment, and the routing of cables from the battery in order to maintain essential services during an incident.

9.5 It is strongly recommended that the temperature of the battery space/compartment is given strong consideration for all installations. To ensure that the batteries are kept within their thermal operating limits, temperature control systems like water cooling systems or heating, ventilation and air conditioning (HVAC) systems should be employed with levels of redundancy to ensure that localised cell temperatures remain within manufacturers guidelines in the most onerous heating condition (e.g. high external atmospheric temperatures with all equipment operating at maximum load). The failure of such temperature control systems should produce alarms for the battery system. Temperature monitoring of the battery compartment is also recommended and this may be linked to early warning alarms as well as fixed fire suppression systems.

9.6 All ventilation and electrical systems within the battery compartment should be capable of being isolated from a safe location outside of the battery compartment. Ventilation systems should safely expel toxic or flammable gases to a safe location.

9.7 The battery and battery systems should be fixed within the battery compartment such that they can endure the maximum predicted vessel motions. Heavy items or items which could cause physical damage to the battery should not be co-located with the battery unless these are retained within the same parameters. Consideration should be given to fixing the battery adjacent to any potential heat source which could result in inadvertent heating of the battery, e.g. exhaust, heavily loaded electrical cabling and direct sunlight.

9.8 The battery location and fixings should ensure that standing water and residues are removed from around the battery and fire-fighting mediums can adequately penetrate the battery casings to extinguish and/or quench a potential fire.

9.9 Consideration should be given to the reduction of combustible materials within a battery compartment, especially those which produce smoke or toxic products in a fire. For certain types of vessel the use of combustible materials within the battery compartment may be prohibited. Dangerous goods should not be stored in a battery compartment.

9.10 The boundaries of the battery compartment should have fire protection to contain a fire in the space of origin and it should be appropriate for the cumulative fire loads within the compartment and the type of vessel (e.g. an A-60 class division). Penetrations through these boundaries should be protected to the same fire protection standard. For domestic vessels, the required fire protection may be defined in the applicable vessel regulations.

9.11 Early identification of a potential lithium-ion battery fire and automated actions prior to an incident are key to preventing thermal runaway and a possible chain reaction between adjacent cells. The battery compartment should be fitted with detectors in accordance with manufacturer's recommendations which are capable of providing early identification of a fire. Possible early identification could involve the monitoring of local cell temperatures or detection of electrolyte solvent vapours. When activated the detectors should initiate appropriate alarms and may automatically isolate electrical systems and ventilation, or activate fixed fire-fighting systems.

9.12 An assessment should be conducted to identify the most appropriate fire-fighting equipment and procedures for the types of fire within the battery space/compartment - such an assessment may consider at what point fire fighting using portable equipment may no longer be appropriate. Both extinguishment and heat removal are fundamental to fire-fighting efforts and because a lithium-ion battery does not contain metallic lithium many of the common fire-fighting mediums can be utilised <u>once the relevant isolations are made</u> (e.g. electrical or ventilation). It is strongly recommended that one or more fixed fire-fighting systems are designed and installed so that these can be operated from a safe location with feedback provided to confirm proper activation. In addition, portable fire extinguishers should be provided to address the potential classes of fire within the battery compartment and the fire loads that they present. For certain vessel types a fire hydrant, hose and suitable nozzle should also be available to access all parts of the battery compartment.

10. Battery Operations and Procedures

10.1 Labels and signs - lithium-ion batteries, high voltage equipment, battery systems and compartments should be adequately labelled using internationally agreed symbols where available. Emergency systems should be appropriately labelled and be clearly visible.

10.2 Logbooks and configuration - it is recommended that a battery logbook is held on board to record the status of the battery and its equipment. The logbook may include: equipment serial numbers and dates of manufacture/installation/testing/expiry, maintenance records, test results, defects, a summary of the battery charge/discharge cycles, etc. Software used for control, monitoring, data logging, alarm and safety systems, which may be part of the battery management system, should be developed using robust and auditable processes. All software within such systems should be version controlled and recorded.

10.3 Operational procedures – it should be ensured that the battery system is never operated outside of its designed scope of assumptions and limitations. Therefore, although a battery system will contain many cascading levels of protective devices, the vessel should not employ operational procedures that rely on these protective devices for a safe condition.

10.4 For vessels utilising electrical power from the battery system for propulsive power or dynamic positioning, operational procedures are considered of prime important to both protect the battery system whilst ensuring that loss of a battery system does not affect the safety of the vessel or its operations. Formal operating procedures should be developed for the operating scenarios expected of the battery, considerations might include failure scenarios (e.g. loss of a cooling system) to ensure that the battery is not inadvertently operated outside of safe parameters – it is expected that consideration of such scenarios may lead to further safety mitigations in the design of the battery system.

10.5 Inspections and maintenance – all inspections and maintenance should be in accordance with manufacturer’s recommendations but should include the testing of all sensors, assessment of the state of health of each cell, recording of the environmental conditions in the battery compartment and assessment of any other relevant factors. Routine inspections may check for physical damage, cleanliness, signs of arcing or increased temperature, correct operation of ventilation and battery protection systems, etc. Maintenance activities should be planned in a vessel’s maintenance schedule. Procedures should be held on board to detail the necessary actions if the battery is at risk of being operated outside of its normal operating envelope (e.g. during extended refit periods, following limited charge periods or following identification of a defect).

10.6 Emergency procedures should be developed for the actions to be taken in all likely emergency scenarios; these may require consultation with an independent body such as a class society. Scenarios may include a battery localised high temperature, activation of a fire detection device, identification of a fire in the battery compartment (a battery fire or another combustible), a medical incident, flooding, violent cell venting, etc. Emergency procedures should be held on board and should include actions to be taken by all stakeholders, including emergency services and salvage teams, to create a safe condition. Emergency drills and training should be routinely conducted for all of the main emergency scenarios.

10.7 An assessment should be made of the possible medical scenarios related to the lithium-ion battery and suitable mitigations should be actioned whether these be pre-emptive (e.g. provision of personal protective equipment) or remedial (e.g. installation of an eye-wash station).

10.8 Crew Training - it is recommended that at no time should there be less than two persons on the vessel who are adequately trained and experienced in all battery equipment and procedures. In addition, all crew should have an awareness of the vessel's emergency procedures regarding the battery.

11. Disassembly and Recycling

11.1 An assessment should be conducted to identify the safety and environmental aspects of disassembling and recycling of a lithium-ion battery system. Consideration should be given to recycling of the by-products from a lithium-ion fire and the used fire-fighting medium.

11.2 Waste disposal must be in accordance with the Waste Batteries and Accumulators Regulations 2009 and The Batteries and Accumulators and Waste Batteries and Accumulators Directive 2006/66/EC.

12. Further Information

BS EN 62281 Safety of primary and secondary lithium cells and batteries during transport

BS EN 62619 Safety requirements for secondary lithium cells and batteries for use in industrial applications

BS EN 62620 Secondary lithium cells and batteries for use in industrial applications

IEC 60529 - Specification for classification of degrees of protection provided by enclosures

UN DOT 38.3 Recommendations on the transport of dangerous goods, manual of tests and criteria

More Information

Marine Technology Branch
Maritime and Coastguard Agency
Bay 2/27
Spring Place
105 Commercial Road
Southampton
SO15 1EG

Tel : +44 (0) 23 8032 9100
Fax : +44 (0) 23 8032 9104
e-mail: marinetechnology@mcga.gov.uk

Website Address: www.gov.uk/government/organisations/maritime-and-coastguard-agency

General Inquiries: infoline@mcga.gov.uk

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Safer Lives, Safer Ships, Cleaner Seas