Lloyd's Register

Working together
for a safer world

Battery installations

Key hazards to consider and Lloyd's Register's approach to approval

Second edition, January 2016

A Lloyd's Register Guidance Note

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1. Introduction

This is the second edition of our guidance to clients on battery installations, covering the hazards associated with them, and Lloyd's Register's (LR's) approach to approving them. This guidance is generic and applies to all electric and hybrid configurations, since batteries can be used in any marine application. It is based on our extensive experience of battery installations on board ships and yachts.

Using batteries to supply ships' power systems can improve efficiency, save fuel and reduce emissions. Battery installations also give a significant reduction in noise and vibration compared to traditional power systems. There are currently no international standards for marine battery installations. However, the International Electrotechnical Commission (IEC) is developing two standards: 62619 and 62620. There are also requirements for transportation of batteries such as the UN 38.3 Recommendations on the Transport of Dangerous Goods – Manual of Tests and Criteria.

Several vessels have already been classed under LR's novel design Rules and the interest in battery installations from shipbuilders and battery manufacturers is continuing to increase.

It is important to note that the range of available cell chemistries makes it unfeasible to have a prescriptive set of rules for batteries. LR recognises that lithium-ion is the most commonly-used type of cell at present, but even within the lithium-ion family there is no standard cell. At the same time, research into battery technology is moving rapidly, so developments in cell chemistry can be expected in the near future.

2. Definitions and abbreviations

Cell

Basic functional unit, consisting of an assembly of electrodes, electrolyte, container, terminals and, usually, separators that is a source of electric energy obtained by direct conversion of chemical energy (IEC 62281:2013).

Battery / battery module

One or more cells electrically connected and fitted in a case, with terminals, markings and protective devices etc., as necessary for use (IEC 62281:2013).

Battery pack

Pack comprised of modules connected to create specific bus voltages.

Protective devices

Devices 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 (IEC 62281:2013).

Secondary (rechargeable) cell or battery

Cell or battery which is designed to be electrically recharged (IEC 62281:2013).

Rated capacity

Capacity value of a cell or battery (Ah) determined under specified conditions and declared by the manufacturer (IEC 62281:2013).

State of charge (SoC)

Available capacity in battery expressed as a percentage of rated capacity (IEC 62660-1:2010).

State of health (SoH)

Reflects the general condition of a battery and its ability to deliver the specified performance compared with a new battery.

Battery management unit

Electronic device that control, manages, detects or calculates electric and thermal functions of the battery system that provides communication between the battery system and upper level control systems (ISO 12405-3:2014).

Battery system

Energy storage system that includes batteries, electrical circuits and electronics (battery management units, contactors, etc.) (ISO 12405-3:2014).

3. Overview of cell chemistries

Mass-produced cells can be categorised as aqueous and non-aqueous. Aqueous batteries include lead-acid batteries and alkaline batteries with an aqueous electrolyte such as nickel-cadmium, nickel-zinc or zinc/silver-oxide. Lithium-ion batteries, which are also a type of alkaline battery, are non-aqueous and therefore present different challenges to aqueous batteries.

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-discharged, safety concerns	Under/over-voltage, thermal runaway

Note: Aqueous lithium-ion batteries do exist but have not yet been commercialised due to poor stability. If their performance can be enhanced to meet that of conventional lithium-ion batteries, this will overcome safety concerns relating to organic electrolytes.

4. Hazards

For any battery installation, hazards should be mitigated so that the residual risk is acceptable compared to that of a conventional power system. This section outlines the areas that should be considered.

Mechanical

Mechanical damage to internal components or circuitry of battery packs can cause thermal runaway or other failures once the batteries are energised. Therefore it is vital that they are transported safely and inspected for damage during installation and through-life. Even after installation, the marine environment can easily lead to equipment damage.

Manufacturing defects can also cause failure. Therefore an appropriate level of quality assurance should be carried out by the manufacturer (see section 6). It is critical that cells are constructed in a clean environment with adequate inspection to detect manufacturing faults at the earliest possible stage.

Where appropriate, mechanical shock needs to be considered, taking into consideration the shock resistance requirements of the installation based on the vessel's concept of operations.

Chemical

Lithium-ion (non-aqueous) cells contain flammable electrolytes, whereas other cells (aqueous) contain water-based electrolytes, causing different behaviour under fire conditions.

Aqueous cells: Water-based electrolytes can release hydrogen gas. The electrolytes are also highly corrosive, so guidance on appropriate PPE should be provided by the cell manufacturer.

Non-aqueous: The electrolytes in lithium-ion batteries can release considerable chemical energy when they combust, the result of which (temperature rise, explosion, etc.) should be stated by the manufacturer. Lithium-ion electrolytes can also produce flammable vapours, although it is possible to use non-flammable electrolytes with some loss of power capability.

In either case, vented gases may be flammable and a hazardous area assessment should be carried out on the battery system and associated spaces on the vessel on which it will be installed. This should include a calculation of the maximum potential energy that may be released under failure conditions.

Electrical

Short-circuiting of batteries can occur at the terminals or internally. Short circuit at the terminals is possible in all types of installations and should be prevented by the physical arrangement of the batteries. Internal short circuit can cause thermal runaway, which is when a cell releases its stored energy via a rapid chemical reaction between the anode and cathode. It is relevant to almost all cell chemistries but, as the severity is determined largely by the amount of stored energy, it is more severe in lithium-ion batteries, which have higher energy densities compared to other chemistries. Apart from physical separation of a battery's electrodes, circuit interrupting devices may also need to be used, such as:

- fuses
- circuit breakers
- thermostats
- positive temperature coefficient devices.

A porous polymer separator which melts at a given temperature can also be used to prevent thermal runaway. However, similarly to a fuse, the cell would need to be replaced in the event of the polymer melting. Thermal runaway can also be caused by small manufacturing defects, so, again, quality assurance of the manufacturing process is vital. Thermal runaway can also raise the temperature of cells adjacent to the defective one, causing a chain reaction within the whole battery installation. This can be mitigated by using dividers, for example.

For batteries arranged in series, the lowest-capacity cell will determine discharge time and the highest-capacity cell will determine the charge time. Therefore the cells must be matched. For Lithium-ion cells, it is not possible to balance them using top-off or trickle charge so this must be done by the power management system. The safe voltage range depends on the cell chemistry and should be determined by the manufacturer. More than 100% SoC will cause rapid failure of the electrodes.

The battery management system should protect against over- or under-voltage.

It is vital that charging is stopped immediately if there is an unacceptable temperature rise, as determined by the manufacturer. Provision should also be made for stopping discharge as close as possible to the cut-off voltage. Charge and discharge cycles affect the proportions of gases that are produced and the applicability and extent of this should be assessed by the cell manufacturer and operator and should be considered as part of the vessel's power management system. Generally, any failure in the battery management system or monitoring of battery parameters should result in alarm or shutdown according to the severity of the associated risk.

Fire

Under failure conditions, the maximum temperature rise of a lithium-ion cell is equal to its volumetric energy density divided by its average specific heat per volume. For a lithium-ion battery of 500 Whl-1 (energy density), for example, this could result in a temperature rise of 1,000 degrees. This calculation excludes the possible vaporisation of volatile components, in which case the energy would be diverted into an explosive pressure increase. For any electrolyte/metal/oxide-assisted fire, there is a temperature at which the cell will self-combust – analogous to auto-ignition point for a fuel. This temperature, which can be determined by accelerated rate calorimetry, should be stated by the manufacturer and it must be ensured, through appropriate monitoring and safeguards, that the chance of the battery installation meeting this temperature is as low as reasonably practicable.

Cell chemistry is an important consideration when choosing fire suppression. Using water on a lithium battery will result in the production of hydrogen. However, a fire could be safely extinguished using salt. This highlights the importance of integration between the battery manufacturer, who is best placed to determine such requirements, and the ship designer responsible for fire suppression systems. Fire testing should be carried out to prove the suitability of the chosen method.

In any case, it is often not feasible for a battery space to be accessed during a fire and this should also be considered when selecting fire suppression and extinguishing methods. After a thermal runaway event, lithium-ion batteries may produce hydrogen gas, carbon monoxide, carbon dioxide and methane, among others. Most of the gases are flammable, and carbon monoxide is toxic. Therefore they will contribute to the severity of any fire and endanger human life.

In a lithium-ion battery, there is no lithium metal present. However, the reactivity of the charged negative electrodes is almost as high as lithium metal itself so metal fire-fighting techniques may be appropriate. Lithium plating can occur on over-discharge and the associated dendrite growth can be a source of ignition. However, over-discharge should be prevented by the installed battery management system.

If a water-based fire-fighting system is selected, the composition of the run-off water must be considered as it may be mixed with hazardous substances from the cells.

Environmental

It is not just fire suppression and containment within the same space as a battery installation that must be considered. Fires in adjacent compartments could also increase the temperature sufficiently to cause ignition of the batteries by raising the temperature of the compartment and subsequently the cells above their safe operating temperature.

Ventilation must be considered with respect to any hazardous substances that may be emitted during normal operation. For lead-acid batteries, there are prescriptive Rules. For other types of battery, an assessment should be carried out using information supplied by the battery manufacturer, to ensure that there is no build-up of dangerous gases.

5. System considerations

Configuration

This guidance applies equally to battery-only systems, where batteries are the only source of power supply, and hybrid systems, where the vessel has two or more types of power source, including the battery installation. For hybrid vessels, LR's Provisional Rules for Direct Current Distribution Systems apply, and consideration is to be given to transitions between power sources, possible operating modes, and the software that is within scope.

Location

Spaces where battery installations are located should have appropriate fire suppression systems for the cell chemistry. The battery space must be categorised as 'Machinery space category A' or as an 'A60' compartment, as determined by the risk assessment carried out. A register detailing the location of all batteries held must be made available on board. Thermal management of the space may be critical to the safety, reliability and performance of the installation. Consideration should be given to the impact on adjoining spaces from reasonably foreseeable failures and, where other equipment is co-located with the battery system, the possible impact on safety and availability should be assessed. The thermal management of the space into which the batteries are to be installed should be assessed, including the criticality of any cooling systems required to ensure reliable operation and to prevent thermal runaway. For any cooling system, the ingress protection (IP) rating of the battery casings should be considered.

Owners may want to consider future cell chemistries which could be used to upgrade to a higher energy density. Any change of cell type or battery arrangement would be treated as a modification under LR's rules and would require an appraisal of the installation. It may not be possible to extinguish fires caused by some installations, in which case it must be possible to contain the fire until the source has been consumed entirely. In this case, overpressure would also need to be considered.

Software

The software used in the control, monitoring, alarm and safety systems for battery installations is critical to safety and must be developed according to LR's Rules. It is important to take note of the requirement for software to be developed using robust and auditable processes.

Human factors

A recent battery installation failure was caused partly by a lack of understanding of the installation by the vessel's staff. It is vital that operators are trained in the operation of the battery management system and understand the implications of any alarms that might occur. An important part of this is provision of appropriate documentation by the manufacturer. The owner of the vessel should also provide clear instructions and training on how to manage any failures of the installation, including an awareness of any hazards that may endanger the vessel or operators.

Through-life management

The cell manufacturer should advise what maintenance is required on the cells, if any, and who should carry the maintenance out. The battery management system manufacturer must, in accordance with LR's Rules, have configuration management processes in place to manage any software, and it is recommended that instructions are available for how the operator should manage any problems that occur. Access should be considered in case the cells are to be replaced.

It is recommended that the battery system manufacturer provides a manual that describes the standard operating procedures and the emergency procedures for the system. This should be kept available on board.

The system manufacturer must have a configuration management / version control process in place to manage the software. It is recommended that instructions are readily available to the operator to manage any problems with the software once installed.

The vessel operator must have documented maintenance procedures for the batteries; and keep maintenance records on board. As a minimum, the following maintenance procedures are to be carried out **annually**:

- inspection of sensors that are critical to operation, safety, or computation of capacity (SoC and SoH) (or calibration, if required by the manufacturer)
- verification (by measurement) of energy storage capacity (in kWh) and SoH (percentage of rated capacity) – for vessels that rely on the battery system as a critical power supply for propulsion.

Since battery life is strongly correlated to environmental conditions, the vessel operator must measure and record the following parameters:

- ambient temperature in the battery room by means of remote monitoring and continuous recording
- other environmental factors that may be identified by the battery manufacturer.

SoC and SoH must be displayed.

6. Lloyd's Register's appraisal process

Lloyd's Register uses an integrated approach to the acceptance of battery installations. With the extensive range of cell chemistries, it is not considered appropriate to use prescriptive rules. To allow manufacturers to adopt new cell chemistries as technology evolves, the type approval process will not be used. Instead, LR will carry out an Approval in Principle for proposed battery management systems and adopt a risk-based approach to accepting specific designs. LR will be involved from the concept design phase in order to assure the safety of the battery installation, not only as part of the vessel's electrical system but as part of the whole ship as a system. This will identify potential safety issues from the outset, preventing the need for changes to be made further along the ship's lifecycle when they become disproportionately expensive. The requirements for LR's risk-based appraisal process can be found in the LR Rules, Part 7, Chapter 14, and further guidance can be found in the ShipRight Procedure – Assessment of Risk Based Designs (ARBD).

Cell manufacturers should follow an acceptable quality assurance system, such as ISO 9001, and LR may survey the manufacturer's works to verify an appropriate level of quality assurance. Battery installations will need to undergo the usual surveys required for classification. Factory acceptance and onboard integration testing will be based on the hazards and resulting risks identified during plan appraisal; all test schedules should be approved by the office conducting plan appraisal before any testing is witnessed by an LR surveyor.

Generally, installations should comply with LR's electrical and control requirements (Part 6, Chapters 1 and 2 of the Ship Rules) and it should be noted that where software is used for essential services or safety critical systems, and is not provided with a hard-wired back-up, the software will be subject to a software conformity assessment in accordance with Part 6, Chapter 1, Section 2.13.2 of the Ship Rules. Where battery installations form part of a DC distribution system, the Provisional Rules for Direct Current Distribution Systems also apply. For Naval ships, both the Rules and Regulations for the Classification of Naval Ships and the Provisional Rules and Regulations for Software to be used in Naval Ships, January 2016, apply.

Appendix – Applicable Standards, Rules and Regulations

UN DOT 38.3 Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria

BS EN 62281:2013. Safety of primary and secondary lithium cells and batteries during transport

BS EN 62619 (DRAFT) Safety requirements for secondary lithium cells and batteries, for use in industrial applications

IEC 62620. Secondary lithium cells and batteries, for use in industrial applications

IEC 61508 Functional safety of E/E/PE safety-related systems

LR Rules and Regulations for the Classification of Ships

LR ShipRight – Assessment of Risk Based Designs (ARBD)

LR's Provisional Rules for Direct Current Distribution Systems

LR Software Conformity Assessment System – Assessment Module GEN1 (1994)

LR Type Approval Test Specification Number 1 (2015.

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