Lithium-ion battery safety primer: for use, storage and disposal

Touchette, Sébastien; Recoskie, Steven; Torlone, Giulio; MacNeil, Dean

For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

https://doi.org/10.4224/40002644

NRC·CNRC

Lithium-ion battery safety primer

For use, storage and disposal

Prepared for the Royal Canadian Mounted Police

Sébastien Touchette

Steven Recoskie

Giulio Torlone

Dean MacNeil

Energy Mining and Environment, Battery Testing and Optimisation

01-06-2021

National Research Council Canada | Conseil national de recherches Canada

Canada

Table of contents

List of tables

List of figures

1 Introduction

This document aims to provide guidance with regards to the use, storage, transportation and disposal of rechargeable lithium-ion batteries as well as emergency procedures involving such batteries. The first section consists of an overview of various rechargeable and primary lithium based batteries to provide context and highlight differences between these batteries, with the focus of this work being on lithium-ion rechargeable batteries. A basic description of the various form factors available and the metrics typically used to describe battery performance is included. The hazards to the battery's health and to users from the battery are also discussed.

The five topics of interest (use, storage, transportation, disposal and emergency response to hazards) are addressed individually in their own sections. Each of these sections begins with a discussions of the relevant hazards and causes of failure before discussing best practices and procedures. The document is concluded by a general summary of the various points to consider.

In this work, the term battery is used in a broad sense for convenience and, unless specified otherwise, includes single cells as well as modules and battery packs.

2 Background

In this section, a brief overview of battery technology and terminology is presented. The goal is to provide the reader with a basic understanding of battery terminology used on the market. The various types of batteries are first discussed, followed by the form factors available and performance metrics commonly used in specification sheets. An overview of the hazards to the battery and from the battery is presented.

2.1 Battery Types

Batteries rely on electro-chemical reactions to produce electrical energy on-demand. When a load is connected to the battery, the flow of electrons from the anode (-) to the cathode (+) is permitted, resulting in a chemical reaction inside the battery. Based on whether or not the reaction used is reversible, batteries are divided into two categories: primary (disposable) and secondary (rechargeable). In both cases, the batteries are named (with a few exceptions) based on the material used to make the cathode (positive electrode)

2.1.1 Primary (disposable)

Lithium primary batteries offer good energy density, long shelf life and better low temperature performance compared to rechargeable lithium-ion. Lithium primary batteries (or simply lithium batteries) will usually be referred to as such by suppliers and not marketed as lithium-ion batteries. Below are some example of Lithium primary batteries that can be encountered:

- Manganese dioxide - $Li\text{-}MnO_2$
- Carbon monofluoride - $Li(CF)_x$
- Iron disulfide - $Li\text{-}FeS_2$
- Thionyl-chloride - $Li\text{-}SOCl_2$
- Sulphur dioxide - $Li\text{-}SO_2$
- Aluminium manganese dioxide - $Li/Al\ MnO_2$
- Lithium iron phosphate - $Li\text{-}FePO_4$ (outdated)

Note that although some of the types listed here use the same or similar cathode active material as lithium-ion batteries, they should not be recharged under any circumstances. Batteries designed as primary, typically do not have the required construction methods (thin electrodes, current collector foils, electrolytes, stability) that are suitable for multiple (hundreds) of charge-discharge cycles required for rechargeable batteries. Recharging primary batteries may lead to severe adverse effects such as fire, explosion or the release of toxic gases. Thionyl-chloride and sulphur dioxide batteries in particular are known for their highly toxic and corrosive content.

2.1.2 Secondary (rechargeable)

In the case of lithium-ion rechargeable batteries, as electrons move from the anode (-) to the cathode (+) through the load, positive lithium ions (Li^+) also migrate from the anode (-) to the cathode (+) within the battery. During charging, power is applied to force the opposite reaction, thus storing energy in the battery.

Common lithium-ion battery types are listed in Table 1 with the various names used to refer to them as well as the chemistry and relevant comments. Although some chemistries have been mostly superseded by newer ones with overall better characteristics, there is no ‘best’ chemistry. Manufacturers will choose the best compromise based on manufacturing constraints, costs and application requirements.

Table 1 : Lithium-ion battery types

Name	Chemistry	Comments
Iron Phosphate, LFP	$LiFePO_4$	This is a popular chemistry for heavy duty use, low cost and stationary storage. It is not usually found in small electronics and portable applications due to its lower energy density (Wh/kg). Although part of the lithium-ion family, LFP cells have different operating voltage (2.5V to 3.7V). Care must be taken to use LFP specific chargers for batteries based on this technology.
Lithium manganese iron phosphate, LMFP, LFP	$LiMn_xFe_yPO_4$	This is a new chemistry that may supersede iron phosphate in the near future. Claims to offer the same advantages but with better energy density. Currently available commercially in 18650 format.
Cobalt, LCO	$LiCoO_2$	Initial cathode used in the first lithium-ion battery. The industry is moving away from this chemistry as it is less stable (lower safety) and higher cost than NMC and NCA.
lithium manganese, lithium manganate, LMO	$LiMn_2O_4$	An early alternative to $LiCoO_2$, but it has a smaller gravimetric energy density and less durability at higher temperature. It has been replaced, in most cases, by NMC.
Lithium titanate, LTO	$LiTi_2O_5$	In this case, the titanate is used as the anode material. The cathode is NMC or manganese. This is a popular chemistry for heavy duty use and stationary storage. It is not usually found in small electronics and portable applications. It can typically be used at much higher recharge rates and has improved safety over other Li-ion chemistries. Although part of the lithium-ion family, LTO cells have very different operating voltage. Care must be taken to use LTO specific chargers for batteries based on this technology.

Name	Chemistry	Comments
Nickel-manganese-cobalt, NMC, NCM, … and other permutations depending on the relative ratios	$LiNi_xMn_yCo_zO_2$	One of two main types of lithium-ion cells available on the current market. The subscripts x,y,z can be varied by manufacturer.
Nickel-Cobalt-Aluminum, NCA	$LiNi_xCo_yAl_zO_2$	One of two main types of lithium-ion cells available on the market. The subscripts x,y,z can be varied by manufacturer.

Some experimental batteries or technologies in development are listed in Table 2. These are not available commercially at this time but the terminology may be encountered when researching batteries.

Table 2 : Future batteries

Name	Comments
Lithium air	This battery uses oxygen (or air) as the cathode and solid lithium metal as the anode. It has the potential for higher capacities but present stability (durability) issues and degrades with oxygen impurities.
Lithium metal	The graphite at the anode is replace with metallic lithium like primary batteries
Lithium sulfur	The cathode is replaced with a sulfur compound and the anode is typically lithium metal. These batteries are used for very high energy density applications (aviation), but have issues with durability and safety.
Solid state lithium	Uses a solid separator such as ceramic along with lithium metal as the anode. Used in high energy density applications and are still in pre-commercial state.

2.2 Cell formats

Regardless of chemistry used, battery packs are assembled from cells which are available in four basic battery formats: coin, prismatic, pouch and cylindrical.

Coin cells (ie: watch battery size) are the smallest format and mostly used for research purposes and small commercial devices. With the exception of very small applications (electronics memory backup, watches, hearing aids, etc.), it is unlikely commercial equipment would require coin cell rechargeable lithium batteries.

Prismatic cells are rectangular prism shaped and are available in many manufacturer-dependent form factors. Although possible, it is unlikely portable equipment would use this format due to the additional weight of the cell can. They are typically used for electric vehicles or large scale energy storage.

Pouch cells are available in all shapes and sizes, making them very popular for a multitude of applications, from electronics to electric vehicles. Due to their low weight, they are particularly popular is small portable devices. Since the pouch is not a structural material, they usually have to be supported and compressed while in application. Furthermore, care must be taken not to damage them during handling. Users are most likely to encounter pouch cells in electronic equipment (cell phone batteries) and devices such as drones and radio controlled vehicles.

Cylindrical cells is one of the most readily available form factor. Although many custom sizes are available, some have become unofficial industry standards. Cylindrical cell formats are usually named by their dimensions. For example, cells of the 18650 format have a diameter of 18mm and a length of 65.0mm. Cylindrical cells are used in many applications, from electric vehicles to grid energy storage and consumer electronics. Individual cells are widely used in vaping devices as well as flashlights, laser pointers and other portable devices. The most readily available formats are 18650, 26650, 20700 and 21700.

2.3 Performance metrics and concepts

In this section, the main metrics used to describe the performance of batteries in specification sheets are explained and a brief description of how they are obtained is given. Some concepts are also explained.

2.3.1 Capacity or discharge capacity

This is typically presented in Amp-hours (Ah) and represents the amount of electric charges that are stored in the battery. Capacity is related by a scale factor to the SI unit Coulombs and not to be confused with Capacitance. When combining batteries in parallel, the resulting capacity is the sum of the individual components' capacities. When batteries are connected in series, the resulting capacity remains unchanged (assuming batteries of equal capacities).

Care must be taken when using capacity to compare different batteries as it does not take voltage in consideration. For example, a 10Ah 14.8V pack has twice the energy of a 10Ah, 7.4V pack even though they have the same capacity. Furthermore, some manufacturer of low cost power packs add capacity of series connected components as well, resulting in a many-fold overestimation of the actual pack capacity.

The capacity of a battery is obtained under certain conditions (temperature, discharge rate) which may differ between batteries being compared and may not represent the capacity available in a specific application. For higher current and lower temperature, the available capacity will be lower.

As batteries age, both in terms of elapsed time (calendar aging) and usage (cycle aging), the capacity will gradually and permanently decrease. Although not permanent, self-discharge and on-board protection electronics will reduce the state of charge of the battery over time. This should be considered when batteries are stored or used in low power applications for long periods of time.

2.3.2 Energy

The energy, or energy capacity, is typically presented in Watt-hours (Wh) and represent the electrical energy stored in the battery. This is related by a scale factor to the SI unit Joules. This is conventionally stated as a calculation of the rated capacity multiplied by the nominal voltage. When combining batteries in series or parallel, the energy of the resulting battery equals the sum of the individual components energy (assuming batteries of equal energy capacity).

The energy of a battery is obtained under certain conditions (temperature, discharge rate) which may differ between batteries being compared and may not represent the energy available in a specific application. For higher current, and lower temperature, the available energy will be lower.

As batteries age, both in terms of elapsed time (calendar aging) and usage (cycle aging), the energy capacity will gradually and permanently decrease. Although not permanent, self-discharge and on-board protection electronics will reduce the state of charge of the battery over time. This should be considered when batteries are stored for extended periods of time or used in low power applications over long periods of time.

2.3.3 Discharge rate, current or C rate

Battery datasheets typically list a maximum discharge rate, which can be expressed as a current (in Amps) or as a C-rate, which is a fraction of the battery's rated capacity in Ah. For example, 0.5C for a 10Ah battery is equivalent to a current of 5A. A maximum rate for short duration (pulse) may also be specified. This will be accompanied by a pulse duration.

Note that the maximum discharge current is not the recommended operating current or the current at which the battery will have the rated capacity or cycle life. Using a battery at the maximum rated current may require special cooling considerations and both the usable capacity and cycle life will be lower than the rated values.

It is also important to keep in mind that most applications draw a constant power. As such, the current drawn from the battery will increase as voltage decreases.

2.3.4 Charge rate

Battery datasheets typically list a maximum charge rate, which can be expressed as a current (in Amps) or as a C-rate, which is a fraction of the battery's rated capacity in Ah. For example, 0.5C for a 10Ah battery is equivalent to a current of 5A. A maximum rate for short duration (pulse) may also be specified. This will be accompanied by a pulse duration.

Note that the maximum charge current is not the recommended operating current or the charge current at which the battery will have the rated cycle life. Charging a battery at the maximum rated current may require special cooling considerations and the cycle life will be lower than the rated value.

2.3.5 Cycle life

The cycle life is the number of charge-discharge cycles a battery can be expected to last before it has degraded to the point where the usable capacity falls below a certain percentage of the initial capacity. Typically, full cycles (between 0% state of charge and 100%) are used and carried out under standard conditions (charge/discharge current, temperature) until the battery has 80% of its initial capacity. The cycle life obtained in practice will be dependent on the application. Typically, the cycle life is reduced through higher temperature as well as higher charge/discharge current. Shallower cycling (ex: between 20% state of charge and 80%) will increase the cycle life.

2.3.6 Balancing

In the case where the battery consists of multiple cells in series (all batteries rated for more than 3.7V), an important function of the Battery Management System (BMS) is to ensure cell balancing. This consists of ensuring each series components (single cells or groups of cells in parallel) are at the same voltage at all times. In theory this is assured by each series component being identical but in practice some cells will charge/discharge slightly faster or slower due to variations in capacity.

Since charge and discharge stops as soon as one of the series elements reaches the maximum or minimum voltage, these small variations are compounded over many cycles if balancing is not performed, leading to a gradual reduction of capacity and a narrowing of the operating voltage range.

2.4 Hazards to the battery

In this section, the various hazards that can affect the safety and durability of lithium-ion batteries are listed in Table 3. A description of the hazards is also presented.

Table 3 : Hazards to the battery

Hazard	Description
Overcharge	Overcharge consists of raising the voltage of one or more cells of the battery higher than the maximum charge voltage. This leads to irreversible reactions inside the cells (such as electrolyte oxidation and material breakdown) and is imminently dangerous in the form of increased internal pressure and temperature. Most commercially available battery packs will have protection against this however, a low quality or mismatched charger, human error (misidentified cell voltages) as well as bad pack design may cause some cells to be overcharged through lack of protection or unbalancing.
Over-discharge	Over-discharge consists of using the battery until the voltage of one or more of its cells is lower than the minimum voltage. This leads to irreversible reactions inside the battery cells (such as lithium plating). Over discharge is not dangerous in itself but leaves the battery permanently changed and potentially hazardous during subsequent charge, even at rated voltage and current. An over discharged battery must be immediately marked for disposal. Most commercially available battery packs will have protection against this however, human error (misidentified cell voltages) as well as bad design or failure of the balancing circuit may cause some cells to be over-discharged.
Overcurrent	Using the battery at a higher current than rated may cause an internal fuse to fail, leaving the battery permanently disabled. In cases where there is no fuse, a high current may cause the battery to heat up. If sustained, this may lead to venting and thermal runaway of the cells. In mild cases, it may not have immediate adverse effects but will greatly reduce the cycle life of the battery.

Hazard	Description
Over-temperature	Heating a lithium-ion battery, either through use or environmental conditions, past a certain point will initiate an exothermic decomposition of the battery material which may lead to a thermal runaway. This is usually around 120ºC but can be as low as 90ºC depending on cell chemistry or state of charge. At more moderate heat levels (60ºC), the battery will remain safe but its shelf and cycle life will significantly degrade.
Under temperature	Care must be taken to avoid storing the battery below the minimum rated temperature. Material dimensional changes may affect the integrity of the battery's cells and its ability to function. Care must also be taken to avoid discharging and charging the battery below the corresponding minimum rated temperature. The minimum charging temperature is, in most cases, much higher than the discharge temperature due to the nature of the chemical reactions taking place. Note that even if above the minimum temperature, a derating typically applies to the currents that can be used.
Physical damage	Lithium-ion cells as well as the electronic circuits used to protect them are vulnerable to physical damage. Cells that are crushed or punctured may react violently. BMS that are subjected to excessive vibration, shock or physically damaged may malfunction.

2.5 Hazards from the battery

There are multiple hazards that a battery may present either due to manufacturing defects, misuse or accidents during handling. These hazards, along with a description, are listed in Table 4.

Table 4 : Hazards from the battery

Hazard	Description
Pressurized content	The content of the cell becomes pressurized as temperature increases. In the event of a short circuit or other fault leading to a temperature rise, the cell may vent a stream of hot gas. If the reaction is too quick, the vent fails to open or becomes obstructed, the cell may burst, catch fire or explode.
Inflammable	The electrolyte in liquid or gaseous form as well as vent gases and gas from thermal runaway in oxygen depleted environments are inflammable. Conditions where these gasses are produced may arise from physical damage to the battery or from events such as short circuit and overcharge.
Chemical	The electrolyte contained in the battery is a volatile corrosive chemical and present an inhalation and contact hazard when released in liquid or gas form. In the event of a thermal runaway, some combustion product gases are corrosive and also present an inhalation hazard as well as a contact hazard if condensed.

Hazard	Description
Electrical	Some battery packs can reach voltage that can cause severe bodily harm (50V or more). Care must be taken when storing, manipulating and using such batteries.
Heat/fire	When misused, the battery may reach temperatures that can cause burns. In extreme cases such as thermal runaway with or without flames, it can ignite adjacent combustible material and/or explode.

3 Use

This section focuses on the use of lithium-ion batteries which consists of charging and discharging in various environments as well as manipulation of the battery and exposure to elements corresponding to its intended use. The hazards to the battery (Table 3) and presented by the battery (Table 4) are discussed in the context of how the battery should be used in the field (3.1) and in the lab (3.2).

3.1 In the field

As opposed to storage, disposal or usage in the lab, where the battery is one of the main consideration, the use of lithium-ion batteries in the field presents a different set of challenges. In such cases, the battery is used in support of an application or activity by personnel who may not be aware of particularities of lithium-ion batteries. Furthermore, the environment in which the battery is used is dictated by the application and may present risk to the battery. In this section, some of the risks are identified and possible mitigations are proposed.

3.1.1 Hazards and causes

Over current and Short circuit

- In the field, short circuit and over-current can happen a number of ways. Using the battery with a low quality, defective or incompatible charger can lead to charging currents higher than the battery's maximum charge current. Incompatible equipment and defective equipment in particular present a risk of an excessive current draw.
- Handling of the batteries may also cause short circuits in cases where contactors are exposed. In good quality packs, this is typically prevented by the protection electronics.
- Special consideration must be given to individual cells, which are usually of a standard format (such as 18650) and can be found in flash lights, laser pointer and other low power equipment. These will be physically compatible with devices that may draw more than the cell's maximum current. Furthermore, these types of cells have exposed terminal which present a short-circuit risk when they are changed or transported as spares.

Overcharge

- Overcharge of batteries is possible when using a low quality, defective, or incompatible charger. Most battery packs have on board electronics that protect the cells from overcharge but these protection circuits may be damaged by a faulty or low quality charger.
- Special attention must be given to loose cells, which are usually of a standard format (such as 18650) and will be physically compatible with chargers that may exceed the cells' charge voltage and current. In particular, LFP cells will be overcharged if used with a lithium-ion charger meant for NMC or other chemistries.

Over-discharge

- Over-discharge of batteries is possible however, most battery packs have on-board electronics that protect the cells from over-discharge. These protection circuits may be damaged but a good quality charger will not attempt to charge an over-discharged battery pack.
- Special attention must be given to loose cells, which are usually of a standard format (such as 18650) and will be physically compatible with devices that may continue to function below the cells' minimum voltage.
- For devices using multiple single cells in series, care must be taken to ensure they are at the same state of charge and of the same brand, model and energy capacity. Otherwise, there is a risk of over-discharging the cell with the lowest capacity or lowest state of charge.

Temperature outside of operating range

- Certain applications may expose the battery to environmental conditions outside of the specified storage or operating temperatures. For example, batteries left in a vehicle or dark container in full sun may exceed the maximum temperature. If the battery is in use, the temperature will rise further. A well designed battery will then stop providing power, thus adversely affecting the task in progress while a lower quality battery may allow usage until cells vent. Similarly, a battery left unprotected in winter may be permanently damaged and unsafe to use.
- Possible damage caused by storage outside the temperature range are unlikely to be detected by a charger and, although some battery packs will not allow operation outside the allowable temperature range, they will typically not remember past exposures or be able to detect any damage caused by these events.
- It should be noted that the maximum rated current is not available for the full operating temperature range. A current derating factor has to be applied as the temperature approaches the extremities of the operating range.

Physical damage and environmental conditions

- Depending on the application, usage of batteries in the field may leave them exposed to physical damage. This includes dropping batteries packs or subjecting them to possible puncture or crushing. Depending on the pack and cell design as well as the severity of the event, this may lead to thermal runaway and violent fires.
- Similarly, exposure to flame, water, salt water, corrosive agents or other environmental factors may affect the health and safety of the battery.

3.1.2 Recommendations

Use good quality batteries and a good quality charger designed for the battery type

- It is recommended to use the charger that was designed for the battery but in the event the pack or cells are of a standard format (BB-2590, 18650, …) many chargers will exist.

- When selecting a charger or batteries, consider a brand's reputation for quality products. Avoid cheaper reproductions as they may contain lower quality components.
- Consider the level of integration with the battery. Some chargers will connect to the battery through CANBus or SMBus to monitor its condition more closely.
- For single cell chargers, a dedicated charging channel per cell is preferable to those that charge cells in pairs. Safety features such as temperature monitoring are also desirable.
- Trickle charging is not recommended for lithium-ion batteries.

Consider the application and operating conditions when selecting a battery

- When selecting a battery, look at the application parameters while keeping in mind there may be deratings at the extremities of the operating ranges. Factors to look at are:
    i) operating temperatures and storage temperature
    ii) Voltage range and maximum current
    iii) Cycle life
- When selecting a battery, consider the environmental conditions it will be used in such as
    iv) humidity
    v) exposure to water, salt or corrosive agents
    vi) exposure to heat or flame
    vii) possibility of falling, crushing or other physical impacts
    viii) vibration
- When selecting a battery, consider the safety risks to users and equipment in the context of the application (egress time, access to first aid and fire suppression …). In general, more energy dense batteries provide longer mission times at the expense of more intense reactions in case of failure.
- Consider looking at standards that align with your intended application to simplify the selection task.

Label loose cells, associated chargers and battery compartment of compatible devices

- Avoid using different models of loose cells of the same or similar format. If multiple devices require loose cells, use a cell model that can satisfy the power requirements of all devices if possible.
- In the event multiple models of cells are required, labelling cell types, devices they are used with and chargers (if applicable) will reduce the chance of mistakes occurring. This also applies to non-rechargeable cells. For example, alkaline 1.5V AA, lithium 3V AA and lithium-ion (rechargeable) 3.7V 14500 have the same physical dimensions but are very different batteries.
- Cells of different model should never be used together in the same device.

Charge batteries prior to deployment

- This ensures the batteries are fully topped up before use and confirms that the chargers are functional.
- On critical non-repeatable tasks, it may be desired to charge/discharge a new battery a few times to confirm it is in good working order.

Do not leave batteries to charge unattended

- Ensure someone is in the vicinity of a charging battery to take action in the event a failure occurs.

Have a dedicated location for charging if possible

- Having all charging occur in one location simplifies monitoring and limits the hazards to a defined area which may be better prepared.
- Clear the area of any flammable components.
- Ensure the area is protected from the elements and physical hazards.
- Ensure emergency response equipment is accessible.

Wait for batteries to acclimatize before charging

- Charging a hot or cold battery is not recommended as it may damage the battery or present a hazard to users. Unless explicitly allowed in the operating instructions, wait until the battery reaches room temperature before charging.
- Keep in mind that this may take a significant amount of time for large batteries, especially if they are kept in an enclosure.

Discontinue use of malfunctioning equipment

- If the battery or charger fails, seems hotter than usual or displays other unusual behaviour, disconnect both the battery and charger. Discontinue use until their functionality can be assessed.

Remove the battery if a device is damaged

- In the event a device is damaged, it is recommended to remove the battery if it is safe to do so. This will protect the battery from potential short circuits and avoid exposing it to a fire that may arise from the damaged equipment.
- If there are signs of damage to a device from a swollen, vented or leaking battery, the device should be serviced before being used.

3.2 In the lab

Using or working with lithium ion batteries in the lab presents unique hazards in addition to those discussed in 3.1. Although the battery is in a controlled environment, it is possibly being used with limited protection electronics and in ways not intended by the original design.

3.2.1 Hazards and causes

Over current and Short circuit

- In the lab, the risk of short circuit is greatly increased as exposed cells or partially disassembled batteries are manipulated, possibly with the use of metallic tools and without their protection circuits.
- Furthermore, batteries are connected to experimental and prototype circuits or devices whose protection circuits, if any, is likely not tested with the same rigour as commercial products.
- When building a pack, cells selected at random are possibly mismatched in terms of age, actual capacity or internal resistance even if they are of the same model. If charged in parallel, this could cause lower resistance cells to receive a disproportionate amount of current, possibly exceeding the maximum.

Overcharge

- When externally charging a pack where protection circuits are absent or bypassed, a significant amount of responsibility lies with the user's knowledge of the pack and equipment. Cells may be overcharged if the configuration of the pack doesn't correspond to the charge voltage used or if the equipment doesn't behave as expected.

Over-discharge

- When discharging a pack where protection circuits are absent or bypassed, a significant amount of responsibility lies with the user's knowledge of the pack and equipment. Cells may be over discharged if the configuration of the pack doesn't correspond to the discharge voltage used.
- Care must be taken when the BMS is powered by the battery. If it is left active, it will discharge the battery over time and may do so to the point where it is over-discharged.

Over Temperature

- In the lab this may occur easily when attempting to solder wires to a battery terminal. It may also occur on prototype devices when the heat dissipation has not been appropriately considered. This includes dissipation from the battery to adjacent components as well as from nearby heat producing electronics to the battery.

Physical damage

- In lab environments, the cells, modules or partly disassembled batteries may be more vulnerable to impact if they are manipulated while exposed and outside of their protective housings.

3.2.2 Recommendations

Always ensure the work area is non-conductive and free of clutter

- When manipulating cells or partly disassembled modules and packs, the risk of short circuit increases greatly. Keep in mind that the aluminum case of prismatic or cylindrical cells is often connected to one of the terminals.
- Do not scatter or stack cells. Cells on the work area should be place in non-conductive carrying trays with individual compartments separating terminals to prevent short circuiting.
- Drape non-conductive isolation blankets over exposed connections of large open modules or packs, and present visible signage of high voltage hazard.

Use non-conductive or coated tools when possible

- Using non-conductive tools (ceramic, plastic …) greatly reduce the risk of short circuiting the battery.
- If metal tools must be used, reducing the exposed conductive surface of the tool (screwdrivers, cutters, pliers …) with electric tape or other insulator reduces the risk of short circuit.

Always have the appropriate protection equipment

- In all cases, protective eyewear should be worn along with a flame retardant and easy to remove lab coat. A face shield can provide added protection if required.
- Depending on the work conducted, it may be desirable to have a fume hood connected to the building's exhaust system. This would serve the dual purpose of protecting the user and containing a possible thermal event.

Remove jewelry and accessories

- Accessories such as jewelry and watches may inadvertently cause a short circuit while the battery is being manipulated.

Avoid using a battery without the battery management system

- Charging and discharging a battery for multiple cycles without a battery management system present may lead to overcharge in some cells as cell balancing will not take place and the charge or discharge will not be cut-off when the voltage of individual cells leaves the safe operating range. For example, a lithium-ion battery consisting of two cells at 4.5V and 2V will still show as partially charged (6.5V out of a maximum of 8.4V) even though one of the cells is dangerously overcharged.
- If charging or discharging a battery without a battery management system, the cycler must monitor individual cell voltages and stop the cycling if the voltage is out of the safe operating range.
- If a battery is used to power a custom circuit or prototype, ensure the discharge is stopped, either by the circuit or battery, when any cell reaches the minimum discharge voltage. Also ensure the current supplied by the battery is limited to values below the maximum rated current.
- If a battery is charged by a custom circuit or prototype, ensure the charge is stopped, either by the circuit or the battery, when any cell reaches the maximum charge voltage. Also ensure the current supplied to the battery does not exceed the maximum charge current.

Confirm the battery configuration and characteristics before charging and/or discharging

- When charging or discharging a battery with laboratory equipment, confirm the charge voltage, discharge voltage and current will not exceed those stated in the datasheet.
- In the case the battery is a prototype or partially disassembled, confirm the cell configuration, cell minimum and maximum voltages and cell maximum current. Ensure they will not be exceeded during the process.

Use caution when cycling batteries

- When designing a new schedule to cycle batteries, have a second qualified individual confirm the settings before use. It is important to have the correct values and safety limits if cycling is expected to be performed unattended.
- Monitor batteries for a time when performing automated cycling on a new battery type or using a new schedule to confirm the execution is proceeding as planned.

Discharge the battery before undertaking high risk tasks (assembling or disassembling a battery, testing a prototype circuit, …)

- Whether it is for disassembly of a pack, welding tabs to a cell, or simply connecting them to a prototype circuit, batteries at low states of charge (0%-30%) are significantly safer.
- In case of high voltage batteries, ensure all service disconnect devices are removed and isolate modules in safe working voltages (less than 50V) first whenever possible.

Avoid using unprotected batteries in parallel if possible

- Although this is done in commercial products, there is typically some investigation performed to ensure cells grouped in parallel are of similar age and capacity or that the maximum current of the pack accounts for some variability amongst cells.
- Never mix batteries of different manufacturer or model in the same pack.

Do not cut more than one wire at a time

- Cutting wires as a group may short circuit the battery as the cutting tool momentarily touches all wires simultaneously.

Use proper welding methods to connect wire or tabs to cells

- It is not recommended to apply a soldering iron to battery terminals. Use a spot welder designed for this purpose or other advanced technologies (ultrasonic, laser and others). The heat of a soldering iron against the terminal is transmitted directly into the battery and may cause a thermal reaction while attempting to work faster to minimize such heating will produce low quality solder joints.

Add batteries to the system only when required

- Principles from "just in time" manufacturing can be applied in the lab to reduce the amount of time spent in the vicinity of lithium ion batteries. If possible, use a power supply to power the system during development, assembly and testing. Only take the batteries from storage when they are ready to be used.
- For high voltage batteries, the series connections of the modules and reinstallation of the safety disconnects should be done last.

4 Storage

This section focuses on the storage of lithium-ion batteries, which consists of leaving them unattended and unused for extended periods of time. The hazards are first discussed (4.1), followed by how they can be mitigated (4.2).

4.1 Hazards and causes

Undamaged lithium-ion batteries at moderate states of charge are unlikely to self-initiate a thermal reaction but some measures must be taken to protect them from external factors to avoid increasing the severity of an unrelated event.

Short circuit

- Short circuits may happen in storage across a single battery or a combination of multiple batteries and conductive surfaces if batteries are not physically constrained in the storage space and terminals are left unprotected. Movement of the cells can be caused by handling errors but also unpredictable events such as ventilation and equipment vibrations or earthquakes.

Over-discharge

- Although not an immediate danger, batteries left in storage too long may self-discharge below the point at which they can safely be re-charged. This is particularly the case with batteries with BMS or permanently attached to devices which constitute a current drain even when stored. These present a possible hazard if recharged at a later date.

Excessive temperature

- High temperature can cause venting of electrolyte from packs/cells, presenting an immediate chemical hazard and may eventually lead to thermal runaway and fire. This can be caused by a thermal runaway in an adjacent battery or by external causes such as a hot storage environment or an unrelated fire.

Electrical hazards

- Partially disassembled batteries or modules not designed to be handled individually may present exposed terminals which, depending on voltage, may present a hazard to the health and safety of personnel accessing the storage.

4.2 Recommendations

Discharge batteries to 30% state of charge before long-term storage

- Aging of batteries is slower at lower states of charge. Storing them in this state will ensure batteries kept for later use maintain their energy capacity as much as possible.
- Reducing the state of charge of a battery greatly reduces the severity of internal or external short circuit and other failures related to the battery, thus ensuring safer storage. This does not render the cell inert however as it still contains flammable electrolyte and enough electrical energy to heat the surroundings.
- Batteries that are at or below 30% state of charge already meet the state of charge criteria for shipping.
- It is not advisable to discharge the battery too low as self-discharge or battery electronics may over discharge the battery during extended storage.
- Note that in some cases, the manufacturer may recommend a state of charge for storage. In such cases, follow the manufacturer's instructions.

Protect battery terminals

- In the case of commercially available portable battery packs and modules such as power banks and laptop batteries, terminals are usually recessed and thus protected from accidental contact. This is not the case for individual cells and other form factors as well as for modules that have been taken out of their original enclosures. A case or holder providing protection against incidental contact with the terminals is recommended. Alternatively, tape can be used to cover the exposed terminals. This will mitigate the risk of short circuiting batteries in storage as well as reduce the electrical hazards to users.

Keep storage area clean

- In order to prevent short circuits and minimise material that could contribute to a fire, keep the storage area free of other items.
- Do not overfill the storage area. Use an additional cabinet if more space is needed.

Implement an inventory management system

- An inventory management system should be in place to identify the batteries. At a minimum, a battery's type (make and model) and manufacture date should be available. This allows potential users to lookup the specification sheets for more details and facilitates replacement of aged batteries when new ones come in. For convenience, additional information such as charger compatibility, battery configuration, charge voltage/current and other relevant information may be included as appropriate.
- A maintenance schedule should be in place for items stored over long periods to monitor their health and top-off charge as required.

- Batteries that are waiting for disposal, are damaged or are in any way unusable should be kept in a different location if possible and clearly marked as such to prevent their use.

Use an appropriate storage environment

- Care must be taken to create an appropriate storage environment. It is recommended to store lithium ion batteries in a dedicated cabinet.
    i) The cabinet should be resistant to high temperature. Although there are purpose build cabinets for lithium-ion batteries, flammable liquid cabinets are also a good choice.
    ii) The cabinet's door should have a latching mechanism to ensure the door remains closed in case of a thermal event.
    iii) Surfaces should be non-conductive to reduce short circuit risks.
    iv) Avoid sharp edges to minimize risk of puncturing or tearing pouch cells.
    v) If possible, the storage cabinet should be connected to your building's fume hood system as venting electrolyte represent a chemical hazard to surrounding personnel.
- Any oxidizers, combustible or flammable material should be kept away from the storage to reduce risk in the event of a fire.
- Cabinet should be kept away from areas that have forklifts or other heavy equipment that may collide with it.
- For EV batteries or large numbers of batteries, it is recommended to store them at least 50 feet from buildings or other flammable entities.
- The location of your storage cabinet should be included in your building's emergency response procedure and documentation.

Avoid storing batteries below ambient temperature

- When batteries stored at low temperature are removed from storage, condensation may form on the batteries which may not be rated for exposure to moisture.

Avoid storing batteries in equipment for extended periods of time

- Some equipment have parasitic loads and drain power even when off. This risks over-discharging the battery.
- Any adverse reaction with the battery also puts potentially expensive equipment at risk.

Avoid purchasing too many batteries

- Having more batteries than required creates unnecessary hazards and increases the storage and maintenance burden.
- Batteries will age and deteriorate even if unused.

5 Transportation

This section focuses on the transportation of lithium-ion batteries and discusses the applicable standards and typical recommendations. The information provided here represents general advices and best practices however, the procedures and regulations of the company used for shipping take precedence. Engage with them early to allow for enough time to acquire any packaging materials required and execute their specific pre-shipping protocols.

5.1 Hazards and causes

Short circuit

- During transportation of batteries, the batteries themselves or other conductive objects are at risk of moving within the packaging, possibly causing short-circuits.

Physical damage

- Transport of batteries may expose them to shock and vibration that may not have been considered in their design. This could affect the structural integrity of the battery and adversely affect its safety.

5.2 Recommendations

Discharge packs and cells to 30% or lower

- Although there is no state of charge limits for small batteries (laptop, …) as carry-on luggage on passenger flights and a state of charge limit of 50% for ground travel, it is recommended to use the lowest common denominator of 30% (air shipping) when practical for simplicity and increased safety.
- This greatly reduces the severity of internal or external short circuit and other failures related to the battery. This does not render the cell inert however as it still contains flammable electrolyte and enough electrical energy to heat the surroundings.
- It is not advisable to discharge the battery too low as self-discharge or battery electronics may over discharge the battery during shipping.

Use rigid outer packaging and individual inner packaging

- Inner packaging separates the batteries from one another. In the case of equipment containing batteries, ensure the inner packaging will prevent accidental activation of the device.

- The use of rigid outer packaging protects the batteries or cells from damage. Preferably, UN approved packaging should be used for new commercial batteries and are required for waste and experimental batteries. These are:
  - i) Drums (1A2, 1B2, 1N2, 1H2, 1D, 1G);
  - ii) Boxes (4A, 4B, 4N, 4C1, 4C2, 4D, 4F, 4G, 4H1, 4H2);
  - iii) Jerri cans (3A2, 3B2, 3H2).
- Ensure adequate clearance is present between the batteries and the outer packaging to account for possible mishandling.

Ensure batteries will remain in place in the package

- Use appropriately sized boxes in combination with filling material to ensure batteries will remain in place in the package in the event they are mishandled during transport. This will reduce the risks of potential short circuits and damage to the batteries.
- Care must be taken to avoid crushing the batteries in an effort to secure them. Padding or cushions should be added between the battery and any clamps or straps used.

Use non-combustible material to separate the batteries

- In case of experimental batteries, it is required to separate the individual batteries with enough non-combustible and non-conductive thermal insulation to protect against the potential heating of one of the batteries.

Verify the state of the batteries received before use

- Inspect the physical integrity of the batteries and packaging for signs of damage.
- Verify that the battery voltage is within the operating range.

5.3 Standards and regulations

The shipping and importing of lithium-ion batteries in Canada is regulated under the Transport of Dangerous Goods (TDG) act. Lithium ion batteries have the following UN numbers and identifiers for dangerous goods:

UN3480: LITHIUM ION BATTERIES

UN3481: LITHIUM ION BATTERIES CONTAINED IN EQUIPMENT
-or-
LITHIUM ION BATTERIES PACKED WITH EQUIPMENT

At a minimum, a UN38.3 certification is required for the transportation of any lithium battery of the above classifications. Care should be taken that providers have this certification for their product. This makes the batteries easier to deploy at a later date and also gives some level of confidence regarding the robustness of the battery. In some cases, an exemption can be obtained for experimental batteries and small batches however, this comes with additional restrictions and is limited to domestic land and sea transport.

Aside from the UN38.3 certification, batteries shipped must:

- Be accompanied by shipping documentation.
- Be properly contained.
- Have the appropriate dangerous goods markings (caution label, UN classification and cargo aircraft only label, See Figure 1).

Figure 1 : shipping labels

With regards to containment methods for land and sea transportation, Transport Canada's dangerous goods regulations refers to Packing Instructions from the UN Recommendation. These are

- Packing Instructions P801 (Appendix A1)
- Packing Instructions P910 for prototype and small batch batteries (Appendix A2)
- Packing Instructions P909 or LP904 when transported for recycling or disposal
- Packing Instructions P908 or LP904 when the batteries are damaged

As a general rule, shipping lithium-ion batteries by air is subject to much stricter requirements and prohibited for prototype, defective and damaged batteries, as well as for batteries marked for disposal or recycling. There are further restrictions for passenger flights, where batteries are subject to size limits and can't be in checked luggage. The International Air Transport Association (IATA) publishes *Dangerous Goods Regulations*, which contains standards for the transport of dangerous goods by air. This is based on the International Civil Aviation Organisation (ICAO)'s *Technical Instructions for the Safe Transport of Dangerous Goods by Air*. Transport Canada's Dangerous goods policies align with the IATA regulations and Individual shipping company will have their own processes for compliance.

Shipping batteries by sea is usually the method of choice for products obtained outside of Canada and the United States as it is less restrictive and cheaper than aircraft. It is regulated by the International Maritime Organisation (IMO)'s International Maritime Dangerous Goods (IMDG) Code.

6 Disposal

This section focuses on the disposal of lithium-ion batteries and discusses the typical recommendations and example of procedures. The information provided here represents general advices and best practices however, the procedures of the recycling company accepting the batteries take precedence. Engage with them early to allow for enough time to acquire any packaging materials required and execute their specific packaging protocols.

6.1 Non-abused batteries with known history or visibly intact

This section applies only to batteries that show no sign of malfunction and where it is known that the battery was not physically damaged and its operation conditions did not exceed the rated values.

6.1.1 Hazards and causes

Short circuit

- Disposal presents a significant risk of short circuits as mixed types of batteries, some of which have conductive surfaces, are placed in the same container. A short circuit in the recycling container may cause a thermal runaway or heat adjacent batteries.

physical damage

- In some cases, especially when disassembling batteries in the lab, cells or batteries in the disposal bin may be vulnerable to tear, puncture or other physical damage. This may cause an internal short circuit or electrolyte to leak.

6.1.2 Recommendations

Contact the recycling company before starting the collection of batteries for disposal

- Starting the collection of batteries with knowledge of the disposal requirements will reduce the risk of time consuming repackaging.
- Keep in mind that the recommendations contained in this document may not align with the recycling company’s process. Always follow their process to avoid having batteries refused.
- It may be advantageous to consider various recycling companies. Since requirements vary from one company to the next, some may align better with your needs.

Seal batteries showing signs of leak, damage or corrosion in a plastic bag

- To avoid potential chemical hazards, it is recommended to seal a battery that shows signs of leaks, damage or corrosion.

Arrange for disposal collection at regular intervals

- Regular collection times prevents batteries marked for disposal from accumulating, thus reducing potential hazards.
- It also limits the amount of time possibly damaged batteries remain in your facility.

Use small plastic containers to collect batteries for disposal

- Keep containers size small. This prevents waste batteries from accumulating for long periods of time.
- Although steel container can withstand higher temperature and are more likely to contain a potential fire, they present a short circuit risk and are vulnerable to corrosion. It is recommended to use plastic containers. If only steel containers are available, line them with plastic bags.

Use vermiculite in larger pails

- It is recommended to add vermiculite to larger pails (e.g. greater than 4 L) of lithium batteries. Use about 3cm on the bottom and add some as the pail is filled. Top off the container with a layer of vermiculite to occupy the empty space.

Fully discharge batteries

- To reduce the risk of thermal runaway, batteries should be fully discharged. This can be done down to the minimum allowable voltage for a battery with protection circuits or to 2.5V or lower for single cells.
- For batteries with complete discharge devices, follow the instructions provided by the manufacturer.
- After discharge, ensure the battery is back to room temperature before adding to the disposal container.

Handle with care

- Ensure disposal is done with care as, even if the battery in hand is robust, the disposal container may contain pouch cells, which are more vulnerable to puncture and tear, or damaged batteries.

Tape battery terminals and other exposed steel

- Use tape (electrical tape preferred) to cover the terminals of the battery. Alternatively, batteries can be bagged individually.
- Ensure that other surfaces through which current could flow (sense wires, bus bars, exposed tabs) are also covered.

6.2 Damaged, abused or batteries with unknown history

Damaged batteries present a heightened risk when handled and stored as well as additional hazards. Extra caution should be used when manipulating and storing such batteries.

6.2.1 Additional hazards

It is important to note that these hazards are due to the damaged state of the battery and that the hazards of healthy batteries presented in 6.1.1 still apply.

Stranded Energy

- Damaged packs or cells may not allow controlled discharge due to protection electronics or passive single action devices (fuses …). In such cases, the battery energy that is no longer accessible is called stranded energy. Depending on the state of charge, this may greatly increase the dangers of transporting and disposing of the battery.

Chemical hazards

- Damaged batteries may leak electrolyte, which is a contact hazard in liquid form and respiratory hazard in vapour form.

Fire hazard

- Electrolyte is highly flammable.
- Damaged batteries may have delayed reactions including thermal runaway, sometimes days or weeks after an incident.

6.2.2 Recommendations

The recommendations below are for damaged batteries and supplement or supersede, as applicable, the recommendations presented in 6.1.2 for healthy batteries.

Dispose of damaged batteries as hazardous waste

- Damaged batteries should not be sent through the used battery recycling or disposal program. Dispose of such batteries a hazardous waste.

Wear appropriate protection equipment

- Always wear gloves, eye protection, fire resistant lab coat and safety shoes when handling damaged batteries. Use additional protection (face shield, respirator …) as required.

Discharge the battery if safe and possible

- If it is safe to do so and if the battery protection circuit allows it, discharge the battery in a safe fireproof environment. This will minimize the danger of future safety events.
- Discharge should be done slow (C/20 rate) to avoid generating heat.

7 Hazardous Situations and Emergency procedures

This section focuses on emergency situations involving lithium-ion batteries. First, the numerous hazards that may be present in emergency situations are discussed. Then, the various types of hazardous situations and emergencies will be described and, in each cases, recommendations of how to deal with them are presented.

7.1 Hazards

Burn

- Whether a cell narrowly averts a safety event, vents or goes in thermal runaway, the resulting remains will be hot (100ºC – 500ºC) and may cause burns.
- In the event of thermal runaway, cells may burst and hot or molten material may be ejected from the battery.

Chemical

- Electrolyte contains strong VOC and can cause severe irritations to the respiratory tract, skin and eyes. Avoid exposure to electrolyte in liquid or vapour form.
- In the event of thermal runaway or fire, toxic and corrosive gasses may be generated. These are battery dependant and may include:
  - Hydrogen Fluoride
  - Carbon Monoxide
  - Carbon Dioxide
  - Lithium Hydroxide
  - Thionyl chloride
  - Bromine
  - chlorine dioxide
  - hydrochloric acid
  - sulfur dioxide
  - sulfuryl chloride
  - Other fluoro-compounds
- As a result of firefighting efforts, the following can be generated:
  - Hydrofluoric acid
  - Strongly acidic waste water

  - Hydrogen from the reaction with water
  - Strongly alkaline waste water

Explosion risk

- The gases resulting from a vent or thermal runaway are flammable and may present an explosion risk as they accumulate in an enclosed space and mix with air.

Fire

- During a thermal event, the battery can reach high temperature with or without flames, which may ignite adjacent combustible material, including other batteries.
- During a thermal event, the cell may burst and eject flaming, molten or hot material thus presenting a fire hazard for surrounding combustible materials.

Compressed Content

- During a venting or thermal event, the cell may burst, sending fragments at high velocity into the surroundings.

7.2 General recommendations and first aid

Have proper fire suppression and first aid equipment on hand

- In case of lithium-ion battery fire, use a fire extinguishing agent that allows the reaction to consume itself while preventing it from spreading, such as water or CO_2; a Class D extinguisher is also acceptable.
- If other combustibles catch fire as result of the battery fire, use the appropriate extinguishing agent to douse these secondary fires; it is important to address each type of fire with the appropriate extinguishing agent.
- First aid kit should include oxygen, eye wash bottle and supplies to treat burns and electrocution related injuries as applicable.

Have lab emergency facilities in line with tests performed. This may include:

- Emergency shower and eye rinse station. Note that these must follow ANSI standards and provide temperature regulated potable water.
- Fire suppression system (emergency shower head or other) above the experiment.
- A metal pail with lid partially filled with sand to quickly isolate a battery when there is reason to believe it may heat up or react. Lid should cover loosely to prevent pressure buildup.
- Proximity of fire hose and fire extinguisher.

Review the Safety Data Sheet or product information sheet

- Prior to working with a battery, review the safety data sheet or product information sheet so that you are familiar with the steps to take in the event of a release and the hazards posed by this particular battery.

Ensure users are aware of risks and procedures

- Users handling lithium-ion batteries should be aware of the potential hazards presented by the battery and the established procedures to follow.
- Users should be aware of the location of first aid and fire suppression equipment.

In case of eye contact with electrolyte, gases, or combustion by-products

- Immediately flush eyes with a direct stream of water for at least 15 minutes with eyelids held open, to ensure complete irrigation of all eye and lid tissue. Get immediate medical attention.

In case of skin contact with electrolyte, gases, or combustion by-products

- Flush with cool water or get under a shower.
- Removed contaminated garments.
- Seek medical attention if necessary.

In case of inhalation of electrolyte, gases, or combustion by products

- Move to fresh air.
- Get immediate medical attention.

7.3 Damaged Batteries

Batteries that have been damaged through handling (dropping, puncturing, scoring, …) or shipping as well as battery packs that show signs of damage are at a heightened risk of failure. Internal short circuit caused by damage to the cell are not necessarily immediate and may develop over days or weeks.

Discharge and dispose of damaged batteries

- Batteries that show signs of physical damage should be discharged and disposed of immediately. If that is not possible, the batteries in question should be placed in separate/secure storage where their temperature is monitored and regular visual inspections are done to inspect for changes in health.
- Perform discharge in a vented fireproof enclosure to minimize the risk to surroundings.

7.4 Hot Battery

This consist of a battery who's temperature has increased for no identifiable reason or that has reached temperatures outside of its operating range. The battery presents an imminent risk of venting, bursting or going into thermal runaway.

Evacuate all personnel from the area

- As soon as it has been determined that a hot battery situation exists, completely evacuate all personnel from the area. The area should be secured such that no unnecessary personnel enter.
- The area should remain evacuated until the battery has cooled to room temperature.

Disconnect the battery from device or short circuit

- If it is safe to do so before evacuating the area, quickly determine if an external short-circuit is present and remove it as quickly as possible. If this was the cause of the heating, the battery will likely cool back down without further issues.
- When evaluating risk, keep in mind that some cell chemistries may enter a thermal runaway reaction above a certain temperature; thus, a cell may continue to heat up and there may be a cascade to other cells.

Dispose of the battery once cooled

- After the hot battery has cooled to normal temperature, the battery should be removed from the work area using appropriate personal protective equipment. The cell or battery should be carefully prepared, discharged, or destroyed in a controlled manner prior to disposal by someone trained to do so.

7.5 Electrolyte leak

This section pertains to the case where a battery is leaking electrolyte. This can happen while the battery remains at room temperature or in a hot cell situation, depending on how much damage was caused to the battery. Note that lithium-ion batteries do not contain much free electrolyte as it is mostly absorbed in the cell material. Very little electrolyte would be present during a leak and it would most likely be detectable by smell.

Evacuate all personnel from the area

- Electrolyte is flammable as well as an irritant for the respiratory tract, skin and eyes. It should not be handled by or around unprotected individuals.

Wear appropriate PPE

- These include eye protection, safety shoes, protective clothing, respirator and insulated gloves.

Dispose of battery and cleaning material

- The battery should be placed in a plastic bag and disposed of as a hazardous waste.
- The cleaning material used to collect the electrolyte should be disposed of the same ways as normal organic solvents.

7.6 Cell Venting

This section relates to the case where a cell in a battery is venting due to excessive internal pressure. At this point, the battery is hot. Venting is the last safety measure before thermal runaway occurs. If the vent fails, the cell may burst. If the venting action is insufficient in counteracting the temperature rise, the cell may go into thermal runaway.

Evacuate all personnel from the area

- The vent gases released are corrosive, toxic and flammable, thus presenting serious hazards to personnel without proper protection equipment.
- Depending on the situation, the cell may still go into thermal runaway, presenting further risk to occupants.
- Keep in mind that in buildings where typical laboratory ventilation is absent, this may affect many sections/floors.

Call the fire department and activate building emergency procedures as applicable

- A battery pack containing a venting cell presents a serious health and safety issue that can potentially escalate in severity.
- In the event the reaction is unplanned and outside of lab containment, it likely presents a risk beyond what is acceptable in typical work environments.

Wear appropriate PPE and work in groups

- In the event trained personnel re-enter the room, they should :
  - wear appropriate protective equipment
  - Never operate alone

Be aware of the hazards and risks as well as the current situation.

Apply fire suppression as needed

- Cooling the battery quickly enough may avoid a thermal runaway and propagation to other cells but this is often impeded by the battery casing.
- One of the main purposes of fire suppression in such case is to prevent secondary fires.
- Vent gasses are highly flammable and may ignite, creating a jet of flames.

- A cell venting is usually at temperatures over 120ºC and may continue heating, presenting a risk of ignition for the surroundings.

Ventilate the area

- Air circulation will be required to dissipate the smell and gasses.

Collect waste

- The vented battery and cleanup materials should be disposed of as hazardous waste.

7.7 Thermal runaway

Thermal runaway is the most severe of cell failures. It refers to the rapid self-heating of a cell due to the exothermic chemical reaction of the highly oxidizing positive electrode and the highly reducing negative electrode. At this point, the reaction is irreversible and the cell will be consumed. This will likely propagate to the rest of typical portable battery packs.

Evacuate all personnel from the area

- The vent gases released are corrosive, toxic and flammable, thus presenting serious hazards to personnel without proper protection equipment.
- Flames and extreme temperatures present a serious fire hazard.
- Bursting cells may eject debris and molten metals at high velocity.

Call the fire department and activate building emergency procedures as applicable

- A battery pack containing a cell in thermal runaway presents an imminent and critical threat to the health and safety of personnel and facility.
- In the event the reaction is unplanned and outside of lab containment, it presents a risk beyond what is acceptable in most work environments.

Apply fire suppression

- Vent gasses are highly flammable and may ignite, creating a jet of flames.
- A cell in thermal runaway can reach temperatures over 900ºC, presenting a risk of ignition for the surroundings.
- One of the main purposes of fire suppression in such case is to prevent secondary fires.
- Cooling the battery quickly enough may avoid propagation to other cells but this is often impeded by the battery casing.

8 Conclusions

Lithium-ion batteries provide a convenient, effective and safe way to store energy for a wide range of applications. Their use has increased significantly over the past years and is expected to continue growing in the near future.

As with other energy sources such as fuels and combustible gases, an understanding of the risks posed by lithium-ion batteries and the situations in which they arise is essential for their safe use, transportation storage and disposal. Furthermore, familiarity with the risks and emergency procedure as well as the implementation of preventative measures help mitigate the impact of adverse events when they occur.

Appendix A : Packaging methods

Appendix A reproduces parts of UN packaging methods for the sole purpose of giving guidance regarding what to expect when shipping lithium batteries. Not only are these regulations are subject to change but individual carriers may have their own policies and regulations.

Appendix A1 : P801

P801	**PACKING INSTRUCTION**	**P801**

The following packaging are authorized, provided that the provisions of **4.1.1.1, 4.1.1.2, 4.1.1.6**, and **4.1.3** are met:

1. Rigid outer packaging, wooden slatted crates or pallets. Additionally, the following conditions shall be met:
    a. Batteries stacks shall be in tiers separated by a layer of electrically non-conductive material;
    b. Battery terminals shall not support the weight of other superimposed elements;
    c. Batteries shall be packaged or secured to prevent inadvertent movement;
    d. Batteries shall not leak under normal conditions of transport or appropriate measures shall be taken to prevent the release of electrolyte from the package (e.g. individually packaging batteries or other equally effective methods); and
    e. Batteries shall be protected against short circuits.

2. Stainless steel or plastics bins may also be used to transport used batteries. Additionally, the following conditions shall be met:
    a. The bins shall be resistant to the electrolyte that was contained in the batteries;
    b. The bins shall not be filled to a height greater than the height of their sides;
    c. The outside of the bins shall be free of residues of electrolyte contained in the batteries;
    d. Under normal conditions of transport, no electrolyte shall leak from the bins;
    e. Measures shall be taken to ensure that filled bins cannot lose their content; and
    f. Measures shall be taken to prevent short circuits (e.g. batteries are discharged, individual protection of the battery terminals, etc.).

Appendix A2 : P910

P910	PACKING INSTRUCTION	P910
This instruction applies to UN Nos. 3090, 3091, 3480 and 3481 production runs consisting of not more than 100 cells and batteries, or to pre-production prototypes of cells and batteries when these prototypes are transported for testing [in accordance with Special provision 310]**.**		
The following packaging are authorized provided that the general provisions of **4.1.1** and **4.1.3** are met: 1. For cells and batteries, including when packed with equipment: Drums (1A2, 1B2, 1N2, 1H2, 1D, 1G); Boxes (4A, 4B, 4N, 4C1, 4C2, 4D, 4F, 4G, 4H1, 4H2); Jerri cans (3A2, 3B2, 3H2). Packaging shall conform to the packing group II performance level and shall meet the following requirements: a. Batteries and cells, including equipment, of different sizes, shapes or masses shall be packaged in an outer packaging of a tested design type listed above provided the total gross mass of the package does not exceed the gross mass for which the design type has been tested; b. Each cell or battery shall be individually packed in an inner packaging and placed inside an outer packaging; c. Each inner packaging shall be completely surrounded by sufficient non-combustible and non-conductive thermal insulation material to protect against a dangerous evolution of heat; d. Appropriate measures shall be taken to minimize the effects of vibration and shocks and prevent movement of the cells or batteries within the package that may lead to damage and a dangerous condition during transport. Cushioning material that is non-combustible and non-conductive may be used to meet this requirement; e. Non-combustibility shall be assessed according to a standard recognized in the country where the packaging is designed or manufactured; f. A cell or battery with a net mass of more than 30 kg shall be limited to one cell or battery per outer packaging. 2. For cells and batteries contained in equipment: Drums (1A2, 1B2, 1N2, 1H2, 1D, 1G); Boxes (4A, 4B, 4N, 4C1, 4C2, 4D, 4F, 4G, 4H1, 4H2); Jerri cans (3A2, 3B2, 3H2).		

packaging shall conform to the packing group II performance level and shall meet the following requirements: a. Equipment of different sizes, shapes and masses shall be packaged in an outer packaging of a tested design type listed above provided the total gross mass of the package does not exceed the mass for which the design type has been tested; b. The equipment shall be constructed or packaged in such a manner as to prevent accidental operation during transport; c. Appropriate measures shall be taken to minimize the effects of vibration and shocks and prevent movement of the equipment within the package that may lead to damage and a dangerous condition during transport. When cushioning material is used to meet this requirement it shall be non-combustible and non-conductive; and d. Non-combustibility shall be assessed according to a standard recognized in the country where the packaging is designed or manufactured. 3. The equipment or the batteries may be transported unpackaged under conditions specified by the competent authority. Additional conditions that may be considered in the approval process include, but are not limited to: a. The equipment or the battery shall be strong enough to withstand the shocks and loadings normally encountered during transport, including transhipment between cargo transport units and between cargo transport units and warehouses as well as any removal from a pallet for subsequent manual or mechanical handling; and b. The equipment or the battery shall be fixed in cradles or crates or other handling devices in such a way that it will not become loose during normal conditions of transport.
Additional requirements • The cells and batteries shall be protected against short circuit; • Protection against short circuits includes, but is not limited to, o individual protection of the battery terminals, o inner packaging to prevent contact between cells and batteries, o batteries with recessed terminals designed to protect against short circuits, or o the use of a non-conductive and non-combustible cushioning material to fill empty space between the cells or batteries in the packaging.

NRC.CANADA.CA • INFO@NRC-CNRC.GC.CA • 877-672-2672 •