

Guide

Guide to Lithium Battery Safety for Space Applications

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Guide to Lithium Battery Safety for Space Applications

Sponsored by

American Institute of Aeronautics and Astronautics

Approved

9 September 2022

Abstract

This document contains requirements and guidelines related to the safety of lithium-ion batteries used in space systems including but not limited to satellites, launch vehicles, interplanetary probes, rovers and landers.

Published by

American Institute of Aeronautics and Astronautics
12700 Sunrise Valley Drive, Suite 200, Reston, VA 20191

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Printed in the United States of America.

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FOREWORD

The AIAA G-136-2022 Guide to Lithium Battery Safety for Space Applications has been developed by a team of battery experts under the auspices of AIAA Standards Steering Committee (SSC).

Lithium-based cells and batteries of the non-rechargeable (primary) and rechargeable (secondary) types are increasingly used in human-rated and non-human-rated space applications. The hazards associated with lithium batteries are catastrophic for the human-rated and non-human-rated systems, although the effects may be different in each category. The AIAA G-136-2022 document is a guide for the safe design, use and disposal of lithium-based cells and batteries for all space applications.

The document focuses on all aspects of battery safety from building and designing the batteries to reducing the risk of catastrophic failures. Features related to ground handling and testing, in-orbit and post-flight operations, and disposal or reuse have been factored into the document.

The document includes the background information on the various chemistries associated with the lithium-based primary and secondary batteries, their hazards, mitigation methods, safe design practices, stringent testing requirements that include qualification as well as flight acceptance tests, test procedures for commonly required tests and safety requirements to be followed for ground and on-orbit, and all space operations.

The document can be tailored to be applicable to any space program where a conscious effort is made to not jeopardize the safety of the crew or space vehicle.

This AIAA Guide document was developed as a result of a series of discussions and reviews by the Lithium Battery Safety for Space Applications (LiBSSA COS), SSC and manufacturers and users.

At the time of approval, the members of the AIAA LiBSSA CoS who participated in the nine year review process of this Guide are listed in the table below (see next page).

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INTRODUCTION

The AIAA G-136-2022 Guide to Lithium Battery Safety for Space Applications is applicable to all lithium-based batteries that are to be used on human-rated and non-human-rated space vehicles including those used to power the vehicle, payloads and equipment batteries. It provides information to the designers of the battery systems that are to be used in human-rated and non-human-rated space vehicles, in equipment to be used in both environments, crew suits, payload experiments, etc. It defines the provisions that may be used to design batteries that are safe for ground personnel as well as crew members to handle and operate during all applicable phases of a space mission including the enclosed environment of a human-rated space vehicle, launch vehicles and in unpressurized spaces adjacent to the habitable portion of a space vehicle. The document provides information on hazards, controls, design evaluation and verification. Evaluation of the design and review of the verification of the results may be completed prior to certification for flight and ground operations.

The standard request was first initiated by NASA and was supported by AIAA since there was no agency-level battery safety requirements document. The effort became independent from NASA after three years although the same team was maintained to complete the document. The team members chosen to support the writing of the standard included representatives of NASA centers that have a battery team, academia, cell and battery manufacturers, government agencies, national labs, industry representatives involved with the manufacturing or installation of batteries in space vehicles for human-rated and non-human-rated environments and standards organizations. The standard did not receive the required number of votes to be published and hence the Chairs decided to convert it to a Guide document.

A significant portion of the information originated from the JSC 20793 with substantial additions from the ground safety recommendations provided by NASA GRC's Guidelines on Lithium-ion Battery Use in Space Applications (NASA/TM-2009-215751), Range Safety Requirements (RCC 319 and AFSPCMAN 91-710), the NAVSEA requirements and more recent recommendations from the NTSB (NTSB/AIR-14/01; PB2014-108867). Test procedures described in this document are mostly based on UL, IEC, RTCA, Range Safety, NAVSEA and NASA (JSC Battery safety standard and other work instructions) certification standards.

1 SCOPE

This document contains guidance related to the safety of lithium-ion batteries used in space systems including but not limited to satellites, launch vehicles, interplanetary probes, rovers and landers.

All aspects of the battery acquisition cycles are addressed including design, testing, integration, handling at the launch site and mission use.

This document is intended for space systems only. Requirements for aircraft may be found in documents such as the RTCA DO311a: Minimum Operational Performance Standards for Rechargeable Lithium Batteries and Battery Systems; and the RTCA DO227a: Minimum Operational Performance Standards (MOPS) for Non-Rechargeable Lithium Batteries.

Compliance with this guidance document ensures that the batteries and battery systems can be expected to reliably perform their intended function(s) safely under conditions encountered in space operations and environments. It is mandatory that battery, spacecraft equipment and spacecraft manufacturers, as well as users, thoroughly understand the guidance for performance, capabilities and limitations of the batteries and battery systems. By doing so, safe operation during all aspects of acquisition, transport, integration, operation, maintenance and disposal may be achieved. Any regulatory application of this document is the responsibility of the applicable government agency or user organization.

May: This verb is used for stating non-mandatory goals and to refer to best practice methods that can be construed as example methods.

Will: This verb is used for stating facts or declaration of purpose.

2 TAILORING

When viewed from the perspective of a specific program or project context, the guidance defined in this document may be tailored to match the actual requirements of the particular program or project. Tailoring may be undertaken in consultation with the procuring authority where applicable.

NOTE: Tailoring is a process by which individual requirements or specifications, standards and related documents are evaluated and made applicable to a specific program or project by selection, and in some exceptional cases, modification and addition of requirements in the standards.

3 TERMS AND DEFINITIONS

For the purpose of this document, the following terms and definitions apply.

Ampere-hour

Ampere-hour or Ah is a unit for the quantity of electricity that is related to coulombic capacity, obtained by integrating current in amperes over time in hours. Used as a measure of battery capacity (abbreviated Ah).

Battery

One or more electrically connected cells, assembled together with or without a container with a single positive and negative terminal. A battery may include intercell connectors, protective and other devices.

Battery System

Is comprised of the battery, the battery charger and any protective, monitoring and alerting circuitry or

hardware inside or outside of the battery. It also includes vents (where necessary) and packaging. Some battery systems may include battery discharge units within the system.

Capacity Retention

The fraction of the full capacity available from a battery under specified conditions of discharge after it has been stored for a specific period of time at a specified temperature. In some primary lithium cells, capacity loss may be inferred from the rate of loss of open circuit voltage of a cell or a battery in storage under constant temperature.

Cell

A single electrochemical unit which exhibits a voltage across its two terminals and is used as a component of a battery. A cell is the most basic unit of a battery.

Cell Capacity

The amount of stored electrochemical energy in the cell available for discharge in units of ampere-hour (Ah) or watt-hour (Wh). The most common representation of cell capacity, C , is in units of Ah. For example, a cell that is nominally fully charged, when discharged to its allowed minimum voltage under nominal conditions at 1 ampere for 1 hour, has a C of 1Ah. Describing the cell capacity in terms of energy using the unit watt-hour (Wh) is preferred under some circumstances. The rates of discharge and charge are frequently specified in terms of C -rate (hour^{-1}) that is defined as current divided by the theoretical current required to charge or discharge the cell in one hour. For example, a 0.5C charging rate (h^{-1}) would charge a battery to half its capacity in one hour.

Charged Battery

A battery that has been fully charged in accordance with the battery manufacturer's instructions or as defined in the design documentation.

Charge Current

Current provided to a cell or battery in the direction opposite the flow of current during discharge.

Charge Retention

See Capacity Retention.

C-Rate

Charging or discharging current divided by the theoretical constant current required to charge the cell in one hour. For example, a $C/5$ rate is a current that exhausts a cell's capacity in five hours.

Current Interrupt Device (CID)

CID is a built-in pressure valve that disables the cell, when the pressure internal to the cell is too high (for example, above 180 psi). The CID is designed to be a non-resettable device.

Discharge

The operation of a cell or battery in providing electrical current to an external electrical load.

Electrode

A structure containing electrochemically active material through which electric current passes.

Electrolyte

A medium in which the transport of ions occurs between the positive and negative electrodes that results in a flow of electrons external to the cell.

Embedded Battery

A battery with one or more cells that is (are) directly attached to housing structure that is enclosing operational components that the battery may be powering.

End-of-Discharge Voltage

A preset lower voltage limit that is defined as indicative of the end of discharge of a cell.

End-of-Life Capacity

The minimum capacity, expressed in Ah, required from the battery from its normal fully charged state, at the end of the life of a mission that the satellite or spacecraft is supporting.

Energy Density

The energy per unit volume (volumetric energy density), expressed in units Wh/L. (Also see Specific Energy).

External Short Circuit

A direct connection between the external terminals of a cell or battery that provides a path for current flow between the terminals.

Fault Tolerance

Property or mechanism that enables a battery system to continue to operate in the event of failure due to the occurrence of one or more faults within the system.

Internal Short Circuit

A direct connection between the cathode and anode electrodes internally in a cell that provides an unintended path for current flow.

Overcharge

Overcharge is the forcing of current through a cell or battery after all the active material has been converted to the fully charged state. In other words, charging is continued after 100% state of charge is achieved.

Overdischarge

Discharge past the voltage recommended by the manufacturer, where the full capacity of the battery has been obtained.

Leakage

Release of liquid or gas from a cell or battery. Leakage is determined by either visual observation or weight loss.

Load

An electrical load is any device which causes current flow when connected to the terminals of a cell or battery.

Open-Circuit Voltage (OCV)

The difference in potential between the terminals of a cell or battery in the absence of an external load, i.e., voltage under no-load conditions.

Operating Life

The maximum period during which cell or battery will meet specific performance requirements.

Operating Voltage

A range of voltage bound by an upper limit and a lower limit within which charging and discharging of a cell is allowed.

Personal Protective Equipment (PPE)

Clothing, head gear, goggles, or other garments or equipment designed to protect the wearer from injury or contact with chemicals and other battery hazards including but not limited to electrical circuits, arc flashes and structural materials.

Positive Temperature Coefficient (PTC) Device

An internal protective device used with some primary lithium and lithium-ion cells to provide hazard protection against high currents or short circuits external to the cell. When the device is exposed to a high current condition, a conductive polymer within the PTC heats up and changes phase to become several orders of magnitude more resistive. After the short or high current condition is removed, the PTC returns to its electrically conductive state. Studies have shown that PTCs have voltage limitations similar to other electronic components and can ignite when activated when exposed to voltages above their threshold value. Once-activated PTCs will activate at lower temperatures and currents during subsequent activations.

Protective Circuits

Protective circuits are any component or circuit external to the cell that are used to protect the cell(s)

or battery from failures. They may include, but are not limited to: fuses, fusible links, PTCs (external only), active circuits, passive circuits, circuit breakers, monitors, etc.

Rated Capacity

Rated capacity is the capacity (measured in ampere-hours) of a cell or battery measured by fully charging it, subjecting it to an external load and discharging to the voltage cut-off point as specified by the manufacturer.

The rated capacity of a cell or battery is the minimum guaranteed capacity at beginning of life, and its unit is Ah.

Solid Electrolyte Interphase (SEI)

A passive film on the electrode surface which spatially separates the electrolyte from the electrode. The SEI is ionically conductive and imparts stability to the cell.

Separator

Electronically insulating material intended to prevent the cathode and anode from shorting, but which permits the transport of ions between the two electrodes in the presence of an electrolyte.

Service Life

The maximum service is the period provided by a cell or battery before it loses 20% of the manufacturer's stated capacity. For primary cells, service life may exceed the shelf life declared by the manufacturer, if the load on the battery in the application is very low.

Serviced Battery

A battery that has been fully prepared and maintained in accordance with the manufacturer's instructions or as defined in the design documentation.

Shelf Life

The maximum period, combined storage and service life that a cell or battery can provide. The cell/battery manufacturer specifies the shelf life. The shelf life is determined by the nature and stability of the components that constitute the cell.

Short Circuit

Short circuits can be of two types – external short circuit and internal short circuit. See definitions for External Short Circuit and Internal Short Circuit.

Specific Energy

The energy per unit mass (gravimetric energy density) expressed in units of Wh/kg. (Also see Energy Density.)

Storage

Time from manufacture/activation of cell/battery until it is placed into service in the spacecraft.

State of Charge (SOC)

An indication of the capacity remaining in a cell or battery compared to its fully charged condition. It is usually expressed as a percentage value (0% to 100%). The fully charged condition or 100% SOC is based on the charge profile recommended by the manufacturer.

Thermal Runaway

Thermal runaway is defined as accelerating release of heat inside a cell due to a series of uncontrollable exothermic reactions manifesting as an uncontrolled increase in cell temperature.

Vent

A rated design feature of a cell or battery which activates to relieve excessive internal pressure.

Venting

The act of releasing liquid, particulates or gas from a cell to prevent the buildup of excessive internal pressure. Visual observation of leakage or measurable weight loss indicates venting.

Watt Hours (Wh)

A unit for the quantity of electrical energy obtained by integrating power in watts over time in hours. It is used as a measure of battery capacity (abbreviated Wh).

4 TECHNICAL OVERVIEW AND GUIDELINES SPECIFIC TO SECONDARY (RECHARGEABLE) LITHIUM-ION BATTERIES

This section begins with a technical overview and then provides design, testing and installation safety guidance for rechargeable Li-ion batteries and battery systems used in a space environment. It applies to Li-ion batteries and battery systems that are used in spacecraft, space systems such as astronaut support equipment, probes and landers, and launch vehicles. For the purpose of this document, a battery or battery system includes the battery cells, charge control electronics, and associated thermal and mechanical subsystems.

4.1 Overview of Secondary Li-Ion Cells

Rechargeable Li-ion batteries, battery systems, and systems with embedded rechargeable Li-ion batteries of various chemical compositions, sizes and construction details are widely used in space applications. Among their desirable characteristics are high energy content per unit weight and volume, low heat generation, low self-discharge rates, a voltage that reflects state of charge (for some chemistries) and long cycle life. Due to their high energy density and known intolerance to electrical, thermal and mechanical abuse, these batteries can present hazards if improperly designed, handled, operated or stored.

4.1.1 Lithium-Ion Chemistry Overview

The general electrochemical and performance characteristics of the Li-ion chemistry are detailed in this section.

Electrochemical Characteristics

Li-ion cells are rechargeable (secondary) cells. Li-ion cells are defined by the lithium ions that shuttle positive charge between two host materials. The lithium resides in the cathode when the cell is discharged and the anode when charged. Numerous materials are sufficiently mechanically and chemically stable to allow the physically small lithium ion to migrate in and out of the material. The anode and cathode are often made from mixtures of multiple materials, resulting in a broad array of chemical “recipes.” In addition, the electrolyte used to promote lithium ion mobility is yet a third part of the cell design which is also a mixture of chemicals. Cells can be made from at least ten different major classes, depending upon the type of chemistry selected for the anode, cathode and the electrolyte. The chemical constituents of Li-ion cells are significantly different from aqueous electrolyte battery types. Li-ion cells have >90% energy efficiency through most of their cycle life, i.e., the energy delivered during discharge is approximately equal to the energy supplied to charge the cell.

Li-ion cells use organic aprotic solvents that are stable up to 4.2 V, and a few are stable up to 5 V. The ability to operate at higher voltages, compared to cells less than 2.5 V for other secondary chemistries, translates into an increased energy density compared to aqueous systems, and fewer series cells are needed for a nominal 28 V bus.

Some organic solvents used in lithium-ion cells are available with freezing points below -80°C and others have boiling points exceeding 200°C. This provides a broad design envelope for cells. With a suitable choice of electrolyte, a wide discharge temperature range between -60°C and 80°C is achievable.

Commercial off-the-shelf (COTS) consumer cells typically remain functional down to temperatures in the -10°C to -20°C range, allowing Li-ion cells to operate at low temperatures. The minimum charging temperature for COTS consumer cells is often 10°C to 20°C higher than the minimum discharge

temperature. High temperature operating limits for consumer cells are in the 40°C to 65°C range depending on the intended consumer application.

The choice of anode and cathode materials defines the cell nominal voltage. The nominal operating voltage of common Li-ion cells is approximately 3.6 V (3.3 V for cells with phosphate-based cathode, and 2.4 V for titanate-based anodes). As of 2022, COTS consumer cells are available with energy densities exceeding 250 Wh/kg. COTS consumer cells are designed for a moderate rate of discharge; for example, full discharge in one hour. It is possible to develop custom cells with capable of >100C discharge rates for pulse power needs; it is also possible to make modest energy density improvements when custom designing a cell for very low charge and discharge rate applications.

The charging protocol is specified by the cell manufacturer by providing a charging current, maximum charge voltage and a cutoff current. The charging protocol begins with a constant current charge using the specified current until the maximum charge voltage is reached. Then, a constant voltage charge is maintained at the maximum voltage until the charging current decreases to the specified cutoff current. Temperature limits are also provided.

During discharge, the manufacturer will typically provide both a maximum discharge current and a minimum cell voltage. The manufacturer will also typically share temperature limits for discharge.

The internal resistance for Li-ion cells varies inversely with cell capacity and temperature. Cell resistance is also very dependent on the internal design choices. Resistance can be quoted as either a direct current (DC) or alternating current (AC) measurement. AC resistance is often measured using a 1 kHz AC signal and is useful for determining the resistance of the non-chemical portion of the cell, including weld and conductor resistances. AC resistance is useful for determining maximum possible currents when choosing fuse or contactor interrupt ratings. DC resistance is more applicable to in-use performance but typically varies by more than an order of magnitude as temperature and state of charge are varied and typically ranges from 50 to 80 mΩ for small format cells (1 to 3 Ah) and 0.6 to 3 mΩ for larger format (>50 Ah) cells.

Under open-circuit storage conditions, Li-ion cells will self-discharge as a function of temperature, age and other factors. Cell self-discharge is generally, but not always, characterized by a monotonic decrease in cell voltage and stored capacity with time. Typical losses in cell capacity due to self-discharge can be >10% per month, when a fully charged cell is stored in a >40°C environment and <2% per month when stored at about 20% SOC in a 0°C environment. Li-ion cells can be stored safely in partially charged states at temperatures below 0°C. In general, irreversible capacity loss during storage is less in a partially charged state and at low temperatures, both of which are defined by the manufacturers.

4.1.2 Common Cell Components

Common cell components found in Li-ion cells are described below:

Active Materials, Separator, and Electrolyte

All Li-ion cells have a positive and a negative electrode. Each cell terminal is connected to an electrode inside the cell: the positive terminal to the cathode, and the negative terminal to the anode. Each electrode is tens of micrometers (tens of microns) thick. The anode and the cathode electrodes are separated from each other by a separator that is porous, mechanically and chemically durable, and most importantly, a non-conductor of electrons. The separator is a microporous polymer or ceramic material to allow free flow of ions such as Li⁺ between the anode and cathode.

The Li-ion anode is usually a form of carbon, namely, coke, natural and synthetic graphite, mesophase carbon microbeads (MCMB), carbon fibers, or a form of lithium titanate and in more recent years, silicon-carbon composites. The cathode is generally a lithiated mixed metal oxide (nickel oxide, manganese oxide, cobalt oxide, mixed transition metal oxides, etc.), or lithiated iron phosphate. Both anodes and cathodes contain additives in the form of binders, conductivity enhancers and diluents that aid in the processing of the electrode, the adhesion of the active material on the electrode and electrode conductivity. The electrolyte in

these cells is made up of a combination of organic carbonates and a salt. The most commonly used salt is LiPF_6 (lithium hexafluorophosphate). Other salts such as LiBOB (lithium bisoxalato borate) or LiBF_4 (lithium tetrafluoroborate) may be used also. Common aliphatic carbonate solvents include ethylene carbonate, propylene carbonate, dimethyl carbonate, and diethyl carbonate.

Cell container

Li-ion cell containers can be of different shapes: cylindrical, prismatic or pouch type being the most common configurations used. Cylindrical cells typically have a spiral wound electrode design. Prismatic containers can be built with stacked electrode sheets, or with an oblong wound electrode design. A third variety is a pouch that has electrode sheets contained in aluminized plastic pouch. Many commercial cylindrical cells are case negative (where the cell case is at the same potential as the cell negative electrodes), but some designs are case positive or case neutral. COTS prismatic and pouch cells are almost always case/container neutral. However, mission needs could result in a custom cell that is not case neutral.

Protective devices

Li-ion cells may contain multiple internal safety protective devices to help prevent over-pressure and thermal runaway of the cell. Common devices include a positive thermal coefficient (PTC) device, current interrupt device (CID), shutdown separator, vent or rupture disks, and fusible links.

A PTC device consists of a material whose conductivity decreases at higher temperatures and the PTC is placed in the header area in the current path to one of the cell terminals. In the event of a high current or over-temperature condition, the material acts as a resistor (or a thermal resettable fuse) and reduces the current through the cell. The cell can often be operated again once it returns to ambient temperature; however, its internal resistance is typically higher than before the PTC was tripped.

The CID is a device that is activated mechanically when the internal pressure of the cell exceeds a preset limit. Pressure buildup can occur when Li-ion cells are overcharged to high voltages or if they exceed their temperature limits. Once activated, the CID mechanically interrupts the current to one of the terminals, similar to a fuse. The CID is typically a non-resettable device.

A shutdown separator is a three-layer polymeric material that has a layer of polyethylene sandwiched between layers of polypropylene. It contains pores which allow the electrolyte and the ions to flow during normal operation, but when exposed to high temperatures, the polyethylene layer melts first, reducing or stopping the ion transport through the separator in that area. The polypropylene layer maintains the separator's structural integrity and electrical insulation where the polyethylene layer has melted. Some commercial cell designs have a ceramic coated separator that is considered to be more robust to internal shorting events.

Many Li-ion cells are housed in a metal can contain a vent or a rupture mechanism that is rated to open and release gases formed during the early stages of abuse, when the internal pressure exceeds a preset value. This device prevents the cell from violently rupturing.

In general, pouch cells do not have a designed vent or rupture mechanism. They tend to swell under various conditions of storage, usage and vacuum environments, and require restraint even under normal atmospheric pressure. The laminated polymer pouch typically ruptures at the terminal feedthroughs or along an edge seal at a relatively low pressure.

High capacity cells may also contain other features such as fusible links to provide additional levels of protection. A fusible link melts at specific currents, disrupting the flow of electric current, which then inhibits any further hazardous conditions caused by an external short.

For all protective devices, it is necessary to understand how they function, what conditions activate the protection, and if there are plausible conditions that render them ineffective or cause false activation.

4.1.3 Cell/Battery Classification

This document covers a broad range of cell/battery designs. These designs are categorized based on both their electrical characteristics (capacity and voltage) and the amount of insight the procuring authority has into the design. This allows some adjustment of testing requirements based on attributes of these categories.

Electrical Classification

In general, higher capacity and higher voltage equates to higher energy and power densities across various Li-ion cell/battery types and operating conditions. Under abnormal conditions, the rapid release of energy from Li-ion cells/batteries may create an increased safety risk to people, hardware and/or facilities. As a result, Li-ion cells/batteries used by the space industry may be classified into the following three categories when assessing safety risk.

Table 3.1: Size Classification of Li-Ion Batteries Based on Voltage, Ah-Capacity and Wh-Capacity

Small: <300 mAh (<1.0 Wh)	Used for memory back-up or small hardware applications
Medium: >300 mAh < 6 Ah; <12 V and 60 Wh	Used in small scale applications such as tablet computers, small portable electronic devices, audio/video equipment, etc.
Large: >12 V and/or >60 Wh	Used as main power source for spacecraft launch vehicle or other high voltage/high capacity applications

COTS, Custom and Configuration-Controlled Cells

The following definitions are used to categorize cells/batteries in one of three categories based on the ability of the procuring authority to understand and control the design of the cell/battery.

- COTS cells and batteries: Any cell and battery that is purchased from a cell vendor or a retailer without any alteration to its commercial design.
- Custom cells and batteries: Any cell or battery that is new or altered by the cell vendor upon direction or request of a procuring authority.
- Configuration-controlled cells and batteries: Any cell or battery design wherein any change to the cell and/or battery dimensions, materials, assembly processes or tooling requires notification of the procurement authority.

4.1.4 Common Hazards

Li-ion batteries present unique safety risks primarily due to their flammable electrolyte and high energy density. The electrolyte in the Li-ion cells contains flammable organic solvents. Under high voltage conditions, they undergo exothermic electrochemical decomposition, leading to the formation of gases including hydrogen, carbon monoxide, carbon dioxide and hydrocarbons. The formation of gaseous products, in conjunction with rising internal temperature due to the exothermic decomposition, and the release of oxygen from some cathodes at high voltages, lead to over-pressure conditions inside the cell resulting in venting and smoke, fire and thermal runaway.

The specific hazards generally considered in a safety risk analysis are shorting, overcharge, overdischarge, high temperature and fire, toxic material release, and high pressure.

Overcharge

Studies have shown that overcharge conditions can lead to the deposition of lithium metal in a dendritic form that can create internal shorts in the cell. The electrolyte in the Li-ion cells contains flammable organic solvents, and under high voltage conditions they decompose, leading to the formation of gases (e.g., carbon monoxide, carbon dioxide and other gaseous decomposition products). This can cause over-pressure conditions inside the cell, leading to smoke and flame if the gases are not vented benignly. Overvoltage conditions can destabilize the cathode causing the release of oxygen that increases the likelihood of a catastrophic failure

Low Temperature Charging

Rapid charging at temperatures below the manufacturer's specification can also cause deposition of lithium dendrites. However, lithium dendrite formation can be avoided if the charge current is lowered per the manufacturer's specification or the voltage is limited to less than full SOC.

Shorting

Shorting can occur by electrical, mechanical and thermal means. The two main short circuit hazards are external shorts and internal shorts. External shorts on Li-ion cells through low and high impedance loads can also result in a rise in the cell's internal temperature followed by venting, fire and thermal runaway. The cell SOC at the time of shorting determines how much energy can be released with the worst outcomes observed at the highest states of charge.

Mechanical means for shorting include compression, breaching of the protective cover and object penetration (nail penetration). Thermal means of shorting may include exposure to heat or charging at low temperatures.

Most Li-ion cells are intolerant to internal shorts especially at or near 100% SOC. Internal shorts can be formed in a few ways. First, due to manufacturing defects, internal short circuits can be caused by metal particles, contaminants and fragments trapped during the manufacturing process, dislodged pieces of active material, and even wrinkles in electrodes or separators that remained undetected during assembly, quality screening and testing, and manifest latently during usage.

Secondly, internal short circuits can be caused by misuse in the field, such as stressing the cells and batteries beyond the manufacturer-specified current, voltage and temperature limits. For example, studies have shown that overcharge conditions may lead to lithium metal deposition (dendrite formation), which can cause internal shorts in the cell. Charging at temperatures below the manufacturer's specification can also lead to the formation of lithium dendrites. Overdischarging can cause the dissolution of copper from the copper current collector onto the cathode, anode and separator, which in turn, may result in two shorting failure modes. One failure mode is by the growth of lithium dendrites, in areas covered by copper deposition, during subsequent charging. The other mode is caused by changes in the affected cell's internal resistance that forces the remaining normal cells in the string to go into an unstable condition more easily.

A third reason for the creation of internal shorts is sustained mechanical damage under dynamic conditions, impact, drop, etc. that can lead to indentation of the cell leading to internal shorts.

Self-discharge can also lead to shorting and is discussed below.

Overdischarge and Self-Discharge

Overdischarge may lead to cell/battery heating but does not in itself cause a catastrophic hazard. Overdischarge causes the electrochemical deposition of copper on the cathode, anode and separator which leads to an internal short between electrodes. Furthermore, under overdischarge conditions, gas formation due to decomposition of electrolyte may occur. In most cases, overdischarge may be a benign event, resulting in a dead cell in multi-cell modules. However, one cell failing due to overdischarge will increase the chance of additional cells being subject to the same process, finally resulting in one or more cells exhibiting thermal runaway behavior. Repeated overdischarge cycles increase the likelihood, and severity, of such issues, but even normal cycling after an overdischarge event may lead to issues once copper dissolution is initiated. The copper deposition on the anode, cathode and separator hinders normal lithiation (intercalation of lithium ions) of the anode and can cause uneven lithiation, dendrite formation and heating resulting in a thermal runaway at some point.

Furthermore, uneven rates of self-discharge between cells may also lead to hazardous conditions in Li-ion batteries. Batteries with cells at different states of charge are at risk for overcharging and overdischarging if cell-level charge and discharge controls are not used. It is not uncommon for Li-ion cells, even those from the same manufacturing lot, to exhibit non-uniform self-discharge rates. This non-uniform behavior often accelerates with calendar life, cycle life, and after environmental testing that leads to unbalanced condition and overdischarge of one or more cells if cell-level (cell bank-level) monitoring is not provided.

High Temperatures and Fire

Li-ion batteries are capable of generating very high temperatures during abuse conditions. Excessive temperatures can cause the cells to leak, vent, catch on fire and explode. Abuse conditions include but are not limited to:

- a) internal and external shorts;
- b) over-the-limit charge and discharge currents;
- c) voltages at the cell-level that are outside manufacturers' specifications;
- d) storing and operating beyond the manufacturer-specified temperature limits;
- e) vibration and shock beyond allowed limits; and
- f) extended storage with the cell voltage below their allowed limiting voltage (usually 2.7 V).

Abusive conditions initiate several exothermic reactions, including decomposition of solvents, anode-solvent and cathode-solvent reactions.

Thermal runaway is the most deleterious form of abuse event. While it is most often caused by overcharging or short circuits (external or internal), it generally occurs whenever the heat generation in a cell exceeds the heat dissipation rate, typically when the cell's internal temperature exceeds 190°C. Thermal runaway is a cascading process consisting of the following steps:

- 1) Loss of the protective SEI layer at 120°C brings the bare carbon surface in direct contact with the organic solvent, triggering an exothermic chemical decomposition reaction between the two, raising the cell's internal temperature above 120°C.
- 2) Solvent degradation, also an exothermal process, occurring above 250°C, further raises the temperature.
- 3) Finally, exothermic decomposition of the cathode, raises the internal temperature (T_{int}) far above 250°C, possibly melting the aluminum current collector (melting point ~660°C) on the cathode and in rare cases, the copper current collector (melting point ~1085°C) on the anode.

Depending upon whether these cascading reactions are localized or widespread, the time-interval between the steps might coalesce therefore separating one step from another during post-thermal runaway forensic analysis might not always discern each step. Protective devices may help prevent thermal runaway, for

example the CID against the pressure increase due to a decomposing solvent and a vent against explosion under certain types of abusive conditions such as overcharge. However, if T_{int} increases faster than the response time of the protective devices, thermal runaway may still occur.

Toxicity and Hazardous Material Release

Li-ion cells contain both hazardous and flammable materials. Under abusive conditions such as overcharge, heating, or external shorting or internal cell shorting, additional hazardous materials, many in the gas phase, may be generated and react with the ambient moisture to produce additional toxic compounds. Hazardous emitted gases may include, but are not limited to:

- Carbonates: Ethylene carbonate ($C_3H_4O_3$), Dimethyl carbonate ($C_3H_6O_3$), Ethyl-methyl carbonate ($C_4H_8O_3$), Propylene carbonate ($C_4H_6O_3$), and Diethyl carbonate ($C_5H_{10}O_3$),
- Gases: Hydrogen Fluoride (HF), oxides of cobalt (CoO_x), oxides of manganese (MnO_x), Carbon dioxide (CO_2), Carbon monoxide (CO), Hydrogen (H_2), Oxygen (O_2)
- Hydrocarbons: Methane (CH_4), Ethane (C_2H_6), Ethylene (C_2H_4), Propane (C_3H_8), Propylene (C_3H_6), and Butane (C_4H_{10})
- Fluorides: Ethyl fluoride (C_2H_5F)
- Oxides of nickel (NiO_x), graphite and carbon

$LiPF_6$ salt reacts with ambient moisture to form HF when released from the cell. HF can be in the gaseous as well as in the dissolved state. In either form, HF tends to react quickly with its surrounding therefore making it difficult to detect. There may be a need to confirm, on a case-by-case basis that the quantity of HF released does not exceed PEL (Permissible Exposure Limit) limits such as in confined space applications.

In a confined space, the solvents and other contaminants vented from a group of cells or battery may have the potential of mixing with the ambient air and forming an explosive mixture.

The hazard posed by the gases vented by a Li-ion cell or battery must be evaluated for its intended application and storage area. In a confined space, the solvents vented from a group of cells or battery may have the potential of mixing with the ambient air and forming an explosive mixture.

High Pressure Release

Li-ion cells and batteries are capable of rapidly generating high pressures during abuse conditions such as thermal runaway due to the breakdown of the electrolyte solvent. Lithium-ion cells are capable of producing several liters (for example, an 18650 cell can produce up to even 12 liters of gas) of gas as a result of a thermal runaway. The vented material can be a mixture of gases and solids. The vented materials must be properly vented to prevent overpressure, escape of flammable/toxic substances as well as allow a path for the gas to expand in so that it can cool off before being vented outside of the battery unit where it could pose a fire explosion danger, especially in a launch vehicle. Safety testing is often needed to confirm that a battery will not explode or otherwise generate shrapnel during abuse conditions, particularly for human-rated applications.

4.2 Hazard Mitigation – Controls

Proper integration of rechargeable Li-ion batteries and battery systems into spacecraft requires collaboration between the battery/battery system supplier, spacecraft designer, and spacecraft integrator and, wherever possible, independent, third-party oversight. Only through this cooperative exchange between all parties of the spacecraft performance requirements and the battery's capabilities and limitations, can an effective and safe integration of spacecraft, avionics equipment and battery/battery system be realized. Abusive conditions can best be minimized through user awareness and good practice and procedures.

Spacecraft designers must ensure that the operational parameters and the environment in which the battery

or battery system is to be used are not more severe than that to which it has been designed and tested. Operation or charging at rates and temperatures exceeding design and test limits, improper maintenance, and improper storage may result in conditions leading to catastrophic battery failure. Additionally, the safety of the spacecraft may be compromised if the battery is not properly sized to provide adequate load power for any critical or essential spacecraft system.

Batteries and cells manufactured with high quality controls tend to be safer because there is less variability in electrical performance and response to an abuse condition. The importance of reliability and safety in spacecraft applications of rechargeable Li-ion batteries and battery systems demands an effective quality control system to be followed by the cell and battery manufacturer.

Some of the manufacturing-related quality-control requirements may be found in quality assurance standards documents such as AS9100 and ISO 9000.

4.2.1 General Manufacturing-Related Guidelines

The following guidelines are related to the quality control processes in cell and battery manufacturing facilities:

- 1) The cell and battery supplier may have in place a recognized quality assurance system approved by the organization- or program-identified committee, officer, national civil aviation or military authority and comply with its requirements for all activities. Quality assurance is the tool by which the purchaser and supplier requirements are satisfied.
- 2) Installers and users may get the Li-ion battery systems certified by appropriate authority for each unique battery design in each unique application. Substitutions to an existing battery with new cell design will constitute a new battery design and require recertification. Successful completion of governing regulations or levied standards constitutes certification of a battery design.
- 3) Cells may be selected from cell manufacturers with an established production or user history.
- 4) The user may screen for and reject counterfeit cells and batteries.
- 5) Li-ion cells used in configuring flight Li-ion batteries may be built from a single cell lot. Cell lot is defined for each battery system as all cells with a common date code manufactured from the same continuous production run. In the case of cells that are not mass-produced, a single lot consists of all cells made with the same sub-components.
- 6) A cell production line audit of the cell design may be conducted for assessment of how well contamination, humidity control, and cell defects are limited in all phases of their cell production processes. High particle counts, contamination and lack of humidity control are known to contribute to the high occurrence of cell failure rates. The first line of defense against these types of impurities, inclusions, and defects is stringent quality control during cell manufacturing aimed at keeping foreign particles and contamination to a minimum. Li-ion cell manufacturers have the challenge of fabricating electrodes and cells in both dry and clean environments.
- 7) The procuring entity may benefit to have a thorough understanding of the cell manufacturing control process, and during the audits, special attention may be given to tests and screening methods used by the cell manufacturers to reduce the repetition of expensive screening tests. Many of the electrode fabrication processes involve cutting, stamping, and slitting that generate particles. Hence, it is very important to select cell designs from manufacturers who have years of proven manufacturing quality and periodically audit them to ensure that high quality processes are maintained.
- 8) Cell and battery designs intended for flight may only be procured from vendors with configuration control processes approved by the procuring entity. Configuration control includes maintaining documentation that enables control and replication of the battery design and all tools, fixtures, machines, instruments, settings, environmental conditions, contaminant mitigation measures, materials, and pass/fail criteria for the production of a unique cell/battery design. This includes

periodic independent verification of tool calibration and the certificates of compliance and/or analyses to meet required specifications for composition, impurities, and properties of materials and components. Configuration control requires complete two-way traceability, which is defined as documentation that demonstrates a solid chain of custody from incoming materials to final assembly and vice versa.

- 9) Cell manufacturers who are under configuration control levied by the procuring entity may have independent material verifications by the cell manufacturer or customer and not rely on a material specification sheet.
- 10) Recognized technical standards may be followed with respect to electronic circuit board workmanship, terminations, wire crimping, interconnect cables, harnessing, wiring, soldering of electrical and electronic assemblies, electrostatic discharge control for protection of electronic components and assemblies, and qualification and performance specification for rigid printed boards.
- 11) Wires may be labeled, color coded, sized or otherwise modified to prevent mis-wiring.

Other common quality controls specific to Li-ion battery manufacturing may include:

- Manufacturing traceability
- Materials specifications to control of cell subcomponents
- Impurity definition and controls, particularly humidity
- Cleanliness standards and particulate contamination prevention
- Uniform coating of active materials
- Burr control
- Burst pressure test for rupture disks, cell cases and battery housings
- Test for cell cases and battery housing hermeticity
- Prevention of damage to electrodes
- Process control of critical machine settings
- Preventative maintenance plans for critical equipment
- Controls during winding or stacking (particularly electrode alignment)
- Tab positioning and stress relief
- Welding and sealing operations
- Inspection requirements and quality control checkpoints
- X-ray or CT-scan for electrode alignment, particulate contamination, tab integrity, weld integrity, safety devices, stack misalignment, insulation materials and wire routing.

4.2.2 Hazard Mitigation – Design Checklist

During the design review process the following critical areas may be addressed by similarity, inspection, analysis, or test when evaluating and demonstrating a design for a space application prior to building batteries for qualification testing. The set of questions below is not intended as an abstract or summary of the standards document. It is a checklist that is intended to help the user:

- a) Electrical Performance: Will the battery system be operated in a way that preserves positive margins for operating voltage, current, temperature and cycle life versus the manufacturer's limits for the cell design?
- b) Thermal Characterization: Will the battery and its subcomponents remain within acceptable temperatures at all phases of transportation, pre-launch and operation, or are heaters or coolers needed? Are the thermal gradients expected across the battery suitable for the intended operating life? Does the thermal design provide the means to isolate the rest of the space system in the event of battery anomaly or thermal runaway? Are thermal protective devices such as thermally actuated circuit breakers or thermostats, heat sinks, heat shunts or active cooling loops needed? Does the

thermal design accommodate for sun and shadow effects, and the higher cell impedance and waste heat expected at end of life? Does the design provide thermal margin for the loss/bypass of a cell? If one cell enters thermal runaway, will the failure propagate to surrounding cells?

- c) Cell/Battery Sizing: Has the cell and/or battery size been optimally designed based on required energy and peak power demands, operating voltage and temperature ranges over the life of the mission, and available envelope volume and mass restrictions? Does the cell capacity selection, and/or quantity of cells incorporated into series and parallel arrays optimized for calendar life- and cycle life-induced capacity loss and cell voltage divergence? Are the cells and the battery matched for all performance requirements including all specified anomaly conditions? Are performance margins appropriate for application requirements?
- d) Charge Control/Charge Monitoring Requirements: Will the cells remain within manufacturer's limits for voltage, current and temperature through the charging phase? Is cell-level monitoring provided for human-rated applications? Is cell-balancing needed?
- e) Mechanical Requirements: Is the battery design robust enough to withstand launch and transportation stresses? Will the battery damage surrounding structures or nearby personnel in the event of an anomaly such as thermal runaway or electrical short?
- f) Environmental Requirements: Are there requirements for EMI/EMC, corona, out-gassing, toxicity or terrestrial concerns such as salt-fog, humidity, fine dust and other environmental requirements associated with space use?
- g) System Interfaces: How does the battery system impact surrounding systems and structure, both during operation, during installation and removal, and during a battery anomaly such as thermal runaway? Is the battery protected from external convective, radiative, or conductive heat sources? Is the battery vent oriented in a direction such that any vented material won't damage the rest of the vehicle? Will an unintended discharge occur when the battery is installed on the vehicle?

NOTE: The battery manufacturer or contractor needs to provide the means to install the battery on the vehicle such that the battery potential does not cause an unintended discharge when it is connected to the bus potential. Provisions in the battery handling plan are needed for installing Li-ion batteries at their operational voltage, i.e., "hot swapping," without damage to the batteries and surrounding equipment. It is generally accomplished by means of a Battery Enable Plug where the battery is first connected to the power bus through a resistor and a relay contact. This allows the battery potential to rise and become equal to the bus potential. Once completed, a second relay contact is closed that bypasses the relay-resistor network. This scheme of connection avoids any sudden inrush of electrical current to the bus and any danger of creating a spark or charring of the connector pins.

- h) Safety Design: What protective measures are needed to prevent high currents, high and low cell voltages, high temperatures and shorting? Are they needed at the cell-level, string-level, or module level? Will the thermal runaway of a single cell not propagate to other cells in the battery or cause catastrophic hazards on surrounding environment?
- i) Battery Testing: What components that are internal to the battery, and ground support equipment are needed to facilitate battery testing? For example, are battery malfunction indicators required?
- j) Transportation, Storage, Handling and Disposal: Are special design provisions or verification testing needed to meet DoT, EPA and other federal requirements?
- k) Safety Assessment: What reliability and/or safety assessment needs to be verified for the battery design including but not limited to FHA, FMEA, SFMEA and FTA?

4.3 Design Guidelines for Cells and Batteries

Measures taken to reduce the likelihood and/or severity of an internal short circuit event to a level acceptable to the program/project include design features at the cell- and battery-level. Safety protection is also

incorporated into the battery charge management design whether incorporated inside the battery housing or by external battery management systems. Careful system integration of the battery may also be considered to minimize the risk of a safety incident to acceptable levels.

The guidelines listed below are intended to minimize the likelihood of an unexpected thermal runaway from occurring.

4.3.1 Cell-Level Design Guidelines

Cell safety relies on good design practices and internal safety devices. The following design practices are intrinsic to the safety of Li-ion cells:

- a) Cells or batteries with an open Consumer Product Safety Commission (CPSC) record for recall may not be allowed for space applications.
- b) Procedures for the distribution, assessment and response of Government Industry Data Exchange Program (GIDEP) alerts may be generated. GIDEP is necessary to ensure that information concerning significant problems involving parts, materials and software that is exchanged by the designer includes the proper utilization of this data. The impetus for generating GIDEP is that it could improve the total quality, reliability, and maintainability of systems and components during the acquisition and logistic phases of the life cycle while reducing costs in the development and manufacturing of complex systems and equipment.
- c) All Li-ion cells, except those with lithium-titanate (LTO) anode, may be cathode limited in order to prevent lithium dendrite formation.
- d) The anode active material may overlap the cathode active material.
- e) The separator may extend long enough to prevent the anode and the cathode from touching each other and shorting.
- f) The amount of separator overlap and length beyond the electrodes may be sufficient to provide margin to accommodate build variation and any movement during environmental testing.
- g) Stress relief may be provided on the internal cell connections used to electrically connect the positive and negative electrodes to the cell terminals. Stress relief allows the tabs and attaching point to the thin foil current collectors to better withstand mechanical, structural and thermal stresses as necessary for the application.
- h) The materials in the cell case and cell header, including any seals used to isolate cell terminals, may be corrosion-resistant to the electrolyte, electrodes and additives used in the cell.
- i) Cell terminals may be sized appropriately to minimize localized heating during worst case charge and discharge current and be mechanically robust.
- j) The cell-to-cell interconnects may be of low impedance so that cell imbalances due to differences in interconnect resistance are insignificant.
- k) The cell-level safety devices may demonstrate a higher reliability than is required by the cell and/or battery design as specified by the procurement authority.
- l) Cells may be designed to leak before burst. As per NASA JSC20793 Rev E, a pressure ratio of 2.5:1 with respect to the vent activation pressure of the cell and the ultimate strength of the cell case, provides appropriate safety factor. A minimum of 1.5:1 safety factor may be acceptable if the leak before burst design is consistently demonstrated for each cell lot and a letter of acceptance and an approval memo is obtained from the structural experts or relevant technical authority for the respective organization.

4.3.2 Battery Design Guidelines

- 1) Safe cells, however, do not guarantee a safe battery. Battery safety relies on good design practices and incorporates the following, as a minimum. On the battery casing, the manufacturer of the battery may identify clearly the battery chemistry, Ah capacity, battery voltage, part number, date of manufacturing, allowed operating voltage and temperature limits, allowed maximum charge and discharge rates, and the manufacturer's identity.
- 2) Batteries may be designed to perform within the manufacturer's specifications for the cells used to build the battery.
- 3) In the case of COTS battery designs, only batteries whose performance and safety have been sufficiently characterized to support safety assessment and validation of the abuse tolerance may be used.
- 4) Battery designs, including battery management system (BMS) may also have at least one-fault tolerance for non-human-rated missions and at least two-fault tolerance for human-rated missions, to prevent the cells from being subjected to off-nominal conditions.
- 5) Cell matching prior to battery assembly may be performed to mitigate state-of-charge (SOC) imbalances capable of adversely affecting battery performance and/or safety due to over-charging or over-discharging.
- 6) Cells may be matched in a battery based on, at a minimum, open circuit voltage, charge retention, internal resistance, and ampere-hour capacity.
- 7) Cell matching and the use of balancing circuits may not constitute rationale for accepting cell lots with poor cell lot uniformity.
- 8) The materials used in the battery and battery system may meet the flammability requirements of the applicable certification authority.
- 9) Contacts between dissimilar metals within the battery may be protected against galvanic corrosion.
- 10) Each cell and cell stack in the battery may be isolated from the battery chassis by at least two layers of electrical insulating material between the cell and the battery chassis.

NOTE: This is particularly important for cells that are case-negative or case-positive by design. If the battery chassis is insulated from the system ground, it is enough to have only one insulation layer between each cell and the battery chassis.
- 11) Each cell may be restrained within the battery as needed to prevent undue expansion, warping, or movement over the life of the battery under all expected environmental conditions.
- 12) Depending on the criticality of the battery application, the number of redundant voltage and temperature sense lines for monitoring may be determined and specified.
- 13) Battery wiring, power leads, and cell-to-cell interconnects may be sized appropriately (including margin) for current and heat carrying capability based on the worst-case currents and temperatures expected for the design in operation.
- 14) All battery and cell voltage sense lines may have a fuse, or be otherwise protected, in the event of an external short.
- 15) Battery terminals that pass through metal battery enclosures may be insulated from the case by an insulating collar or other effective means.
- 16) Battery connectors may be selected per industry standard and be mechanically robust and capable of withstanding multiple matings/dematings.
- 17) Main power pins or sockets of opposing polarity may be separated to minimize the risk of accidental shorting.