AEROSPACE REPORT NO.
TOR-2013-00295

Architectures for Lithium Ion Based Power Subsystems

June 3, 2013

Valerie J. Ang
Energy Technology Department
Electronics and Photonics Laboratory

Prepared for:

Space and Missile Systems Center
Air Force Space Command
483 N. Aviation Blvd.
El Segundo, CA 90245-2808

Contract No. FA8802-09-C-0001

Authorized by: Systems Planning, Engineering, and Quality

Developed in conjunction with Government and Industry contributions as part of the U.S. Space Programs Mission Assurance Improvement workshop.

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Executive Summary

This document was produced under the guidance of the Mission Assurance Improvement Workshop during the 2012-2013 year. A muti-discipline team was assembled from the Aerospace industry to develop guidelines that define power subsystem architectures for lithium ion batteries for different class missions. These architectures also consider implementation of lithium ion protection features. This document is intended to provide the satellite developer with guidelines that define the essential design considerations and verification tests needed to assure that a space vehicle has the capability to meet full mission while preventing, surviving, and recovering from power subsystem fault conditions.

Implementation of lithium ion batteries requires a system level approach for mission assurance. A variety of power subsystem architectures that are currently used in satellite systems will be addressed. The performance characteristics of lithium ion cells differ significantly from prior satellite battery technology. The cell's intolerance to overcharge typically mandates the need for additional charge management electronics to insure safe operation and handling, high reliability, and long life. Furthermore, the power subsystem architecture needs to be able to robustly respond to, prevent, and recover from a depleted battery due to lithium ion's limited ability to withstand over discharge. Proposed solutions will be provided for these two key electronic interfaces with the battery. Design features and performance characteristics for two of the most common cell chemistries used in satellite systems to date will be discussed. Lastly, safety regulations and design approaches to ensure safety are discussed for all phases of pre-launch activities. As our understanding about lithium ion implementation grows or new lithium ion chemistries are adopted by the space community this guidebook will be updated.

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This document has been produced as a collaborative effort of the Mission Assurance Improvement Workshop. The forum was organized to enhance mission assurance processes and supporting disciplines through collaboration between industry and government across the US space program community utilizing an issues-based approach. The approach is to engage the appropriate subject matter experts to share best practices across the community in order to produce valuable mission assurance guidance documentation.

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1. Introduction

1.1 Purpose

Lithium ion batteries are fast becoming state-of-the art technology for highly reliable United States government spacecraft applications. Lithium ion technology provides the highest energy density for rechargeable batteries, with good rate capability and the highest efficiency. This leads to lighter weight batteries with reduced volumetric requirements. Due to its unique chemistry, implementation of this technology may require modification to prior spacecraft architectures that used nickel hydrogen technology. Specific challenges surrounding the inability of lithium ion cells to tolerate overcharge and over-discharge are discussed. This document gives consideration to a variety of power subsystem architectures and provides an approach to safely implement lithium ion technology.

1.2 Scope

This report provides guidelines for incorporating lithium ion batteries into unmanned military spacecraft. It assesses a wide variety of power subsystem architectures and evaluates for each the implementation of lithium ion technology. It will consider pertinent topics at the system level, power subsystem level, battery level, and cell level for lithium ion designs. As required, it will treat Geosynchronous Earth Orbit and Low-Earth Orbit missions as distinct space applications. Considerations for how these features are tested at the unit and spacecraft level are provided. It will address guidelines for high reliability Class A missions and lower reliability missions. A separate safety section is provided to discuss the unique requirements for lithium ion designs.

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2. Applicable Documents

MIL-STD

MIL-HDBK-343	Design, Construction, and Testing Requirements for One of a Kind Space Equipment
MIL-STD-882	Department of Defense Standard Practice: System Safety

AIAA

AIAA S-122-2007	Electrical Power systems for Unmanned Spacecraft
AIAA S-080-1998	Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

NASA

NASA/GRC-M8100.006	Battery Safety and Design Manual for Payloads
NASA/NPR8715.7	Expendable Launch Vehicle Payload Safety Program
NASA/TM-20090215751/NESC-RP-08-75/06-0699-I	Guidelines on Lithium-ion Battery Use in Space Applications
NASA-STD 8719.24	NASA expendable Launch Vehicle Payload Safety Requirements
NASA NPR 8705.4	Risk Classification for NASA Payloads

SMC

SMC-016	Test Requirements for Launch, Upper-Stage Vehicles
SMC-017	Lithium Ion Batteries for Spacecraft Applications

The Aerospace Corporation

TR-2006(1455)-1	Lithium Ion Life Expectancy Verification Guidelines for TSAT
TOR-2007(8583)-6690	Weibull-Based Life Test Scenarios
TOR-2010(8591)-6	Test Like You Fly: Assessment and Implementation Process

Air Force

Air Force, 30th Space Wing	Joint 45 SW/SE and 30 SW/SE Interim Policy Regarding EWR 127-1 Requirements for Systems Safety for Flight and Aerospace Ground Equipment Lithium-Ion Batteries
AFMAN-24-204	Preparing Hazardous Materials for Military Air Shipments
AFSCM-91-710	Range Safety User Requirements Manual Vol 3 – Launch Vehicles Payloads, and Ground Support Systems Requirements
AFSCM-91-710	Range Safety User Requirements Manual Vol 6 – Ground and Launch Personnel, Equipment, Systems, and Material Operations Safety Requirements

United Nations

ST/SG/AC.10/11/Rev.5/Amend.1	Section 38, Lithium Metal and Lithium-ion Batteries, UN Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria

Federal

49 CFR	Code of Federal Regulations Title 49, Transportation, Subtitle B, Chapter 1 Pipeline and Hazardous Material Safety Administration

3. Definitions/Acronym List

3.1 Operational Definitions

For the purpose of this document, the following terms and definitions apply. The document source of definition is provided where applicable.

3.1.1 Acceptance Tests

Vehicle, subsystem, and unit tests conducted to demonstrate that flight hardware is free of workmanship defects, meets specified performance requirements, and is acceptable for delivery ***[SMC-016]***.

3.1.2 Actual Battery Capacity

Beginning of life (BOL) capacity that is available in ground test under the expected on-orbit operating conditions ***[AIAA S-122]***.

Note: Actual battery capacity may be either higher or lower than rated capacity. Actual capacity is determined at specific operating conditions of temperature, age, and load. It may be determined by analysis where sufficiently proven models exist and have been accepted. On orbit measurement of actual capacity generally involves complete discharge of the battery.

3.1.3 Autonomous Load Shedding

Autonomous load shedding (ALS) is a response to a bus undervoltage condition. All non-critical bus loads are turned off and latched off automatically and can only be re-enabled by ground command. Critical loads are turned off but not latched off and will automatically turn on when the primary bus is above minimum operational voltage.

3.1.4 Battery

A battery is an assembly of battery cells or modules, from a single-cell lot, electrically connected (usually in series) to provide the desired voltage and current capability. Generally, the cells are physically integrated into either a single assembly (or battery) or into several separate assemblies (or modules). The battery may also include one or more attachments such as electrical bypass devices, charge control electronics, heaters, temperature sensors, thermal switches, and thermal control elements ***[SMC-017]***.

3.1.5 Battery Depth-of-Discharge (DOD)

The battery Depth-of-Discharge (DOD) is the ratio of the number of watt-hours removed from a battery for a defined charge voltage-current profile, discharge load profile, and temperature profile to the battery rated (or nameplate) energy E(Wh), times 100. For a lithium-ion battery, the DOD must be specified at a state-of-charge (SOC) operation or a voltage that relates to SOC operation ***[SMC-017]***.

$$\text{Battery Depth-of-Discharge (\%)} = \left(\frac{E(Wh)_{\text{REMOVED}}}{E(Wh)_{\text{RATED}}} \right) \text{X } 100$$

Note: For batteries that are subcharged, i.e., not recharged to full energy, DOD is the percentage of energy expended in a discharge from the subcharged point. For example, a battery that is subcharged to 70% SOC and then cycled down to 40% SOC is considered to have cycled over 30% of its energy, and the DOD is 30%.

3.1.6 Battery Energy

Launch, transfer orbit, and on-orbit battery energy and energy reserve requirements are flowed down from the Electrical Power Subsystem specification for the entire mission life. Battery energy is equal to the integral of the product of discharge current and voltage, where Id, a positive value, is the discharge current, and Vd, a positive value, is the discharge voltage. The limits of integration are from the start of discharge to either the minimum power subsystem battery voltage limit, or the point at which the first cell reaches the lower cell voltage limit, or when the defined time duration is reached. This is a point-in-time energy value that is measured at a defined charge voltage-current profile, discharge load profile, and temperature profile. Battery discharge can be accomplished with constant-current discharge; however, constant power discharge is the preferred method if it more closely simulates spacecraft power ***[SMC-017]***.

$$\text{Battery Energy (Wh)} = \int I_d V_d \, dt$$

3.1.7 Battery SOC (SOC)

The Battery SOC (SOC) is the ratio of the number of Wh present in a battery for a defined charge voltage-current profile, discharge load profile, and temperature profile to the rated energy E(Wh) of the battery, times 100 ***[SMC-017]***.

$$\text{Battery State-of-Charge (\%)} = \left(\frac{E(Wh)_{\text{PRESENT}}}{E(Wh)_{\text{RATED}}} \right) \text{X } 100$$

3.1.8 Battery Capacity

Battery capacity is measured in units of ampere-hours (Ah). Battery capacity is equal to the integral of the discharge current, where Id is a positive value. The limits of integration are from the start of discharge to either the minimum power subsystem battery voltage limit, or the point at which the first cell reaches the lower cell voltage limit, or the defined time duration is reached. This is a point-in-time capacity value that is measured at a defined charge voltage-current profile, discharge load profile, and temperature profile ***[SMC-017]***.

$$\text{Battery Capacity (Ah)} = \int I_d \, dt$$

3.1.9 Bus Voltage

Nominal DC voltage at the main bus or at any distribution point ***[AIAA S-122]***.

3.1.10 Catastrophic Hazard

A catastrophic hazard is a hazard that could result in one or more of the following: death, permanent disability, irreversible significant environmental impact, or monetary loss equal to or exceeding $10M ***[MIL-STD-882]***.

3.1.11 Cell Activation

The addition of electrolyte to a battery cell constitutes cell activation and starts the clock on cell, module, and battery service life. It is used to define the start of battery shelf life ***[SMC-017]***.

3.1.12 Cell or Battery Cell

A cell is a single-unit device within one cell case that transforms chemical energy into electrical energy at characteristic voltages when discharged. Battery cells can be directly connected (usually in series) to form a battery. Battery cells can be connected in series or parallel to form a module; in such cases, the modules are connected (usually in series) to form a battery ***[SMC-017].***

3.1.13 Cell Balance Electronics

Small differences in self-discharge rates and parasitic loads among series connected cells result in unequal cell voltages. Cell balance electronics is used to equalize all cell voltages within a battery. The process of cell balancing may be continuous or periodic. Use of cell balance electronics can maximize the energy and lifetime of a lithium ion battery.

3.1.14 Cell Bypass Switch

Cell battery switch, once activated, provides an alternate low impedance path around a cell so that battery charge and discharge can continue in the presence of a failed or degraded cell. The cell remains electrically connected in parallel with the bypass device. A cell bypass switch is a means to avoid a single point failure in a battery. Also refer to cell isolation switch.

3.1.15 Cell Design

A cell design is built to one set of manufacturing control documents that define material composition, dimensions, quantity, process, and process controls for each component in the cell. A change in cell design is considered a different cell design that requires a separate qualification. A change in cell design includes, but is not limited to, the following ***[SMC-017]:***

- Positive electrode composition, raw material (including binder), loading density, foil, dimension, or process change
- Negative electrode composition, raw material (including binder), loading density, foil, dimension, or process change
- Electrolyte composition
- Separator composition or dimension
- Cell stack or cylindrical wrap dimension or compression
- Cell case size
- Change in cell or raw material manufacturing location
- Terminal seal

3.1.16 Cell Isolation Switch

Cell isolation switch once activated provides an alternate low impedance path around a cell so that battery charge and discharge can continue in the presence of a failed or degraded cell. The switch is designed to provide a make before break transition during actuation. Once actuated the cell is isolated from the electrical circuit. A cell isolation switch provides a means to avoid a single point failure in a battery. Also refer to cell bypass.

3.1.17 Cell Lot or Battery Cell Lot

A cell lot or flight battery cell lot consists of a continuous, uninterrupted production run of cells, which consists of anode, cathode, electrolyte material, and separator, from the same raw material sublots with no change in processes or drawings. A flight battery or lithium-ion cells produced in a single lot should be procured, stored, delivered, and tested together to maintain a flight battery or single lot definition.

It is the intent that all cells in a flight battery contain a single lot of cells that are all exposed to the same duration of temperature exposure and electrical cycles. Any deviation from this requirement will require a waiver. Factors that are important in obtaining a waiver include charge control architecture, capacity fade and resistance change as a function of temperature storage and electrical cycling, distribution of capacity fade, and resistance change demonstrated in life test ***[SMC-017]***.

3.1.18 C/n Charge or Discharge Current (C-Rate)

The constant charge or discharge current for a battery is defined as C/n, or C-rate. C is the cell-level nameplate (or rated) capacity in ampere-hours (per vendor’s criteria), and n is any value for elapsed time measured in hours. For example, a discharge current of C/2 for a 20 Ah rated cell is a discharge current of 10 A ***[SMC-017]***.

3.1.19 Cold Storage

Cold storage, for batteries that are not in use, is long-term storage where the temperature and humidity environments are controlled, and temperature is below ambient temperature ***[SMC-017]***.

3.1.20 Commerce

Trade or transportation in the jurisdiction of the United States within a single state; between a place in a state and a place outside of the state; that affects trade or transportation between a place in a state and place outside of the state; or on a United States-registered aircraft ***[49 CFR §171.8]***.

3.1.21 Critical Hazard

A critical hazard is a hazard that could result in one or more of the following: permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, reversible significant environmental impact, or monetary loss equal to or exceeding $1M but less than $10M ***[MIL-STD-882]***.

3.1.22 Critical Loads

Critical loads (also known as essential loads) are those that are essential for minimum controllability and commandability of the spacecraft.

3.1.23 Dead Bus

A dead bus is an anomalous condition where a spacecraft's primary bus collapses to a voltage below the minimum operational level (including zero volts) following the loss of primary power (usually solar array power) and depletion of available battery charge. The root cause leading to a dead bus may trace to multiple failures, faulty or corrupted software, common flaws in redundant subsystems, unforeseen design errors, inadequate testing, ground operator errors, or other unforeseen circumstance.

3.1.24 Dead Bus Recovery

Dead Bus Recovery (DBR) begins at the lowest level of under-voltage response. DBR is the autonomous restoration of power to the primary spacecraft bus following the sequential occurrence of a dead bus condition and the return of solar array illumination. DBR requires autonomous load shedding to maximize the available power for critical equipment and battery charging.

3.1.25 Depleted-Battery Prevention

Depleted-Battery Prevention (DBP) applies to spacecraft batteries that can be permanently damaged by complete discharge. DBP must occur before the occurrence of a dead bus (c.f. dead bus). (Note: DBP for lithium-ion batteries automatically disables discharge capability below a specified minimum SOC. DBP for nickel-hydrogen batteries that have non-resettable cell bypass devices is accomplished by either disabling battery discharge or reducing the battery discharge current to value below the activation threshold of the bypass device.)

3.1.26 Design Verification

All activities including test, analysis, simulation, and inspection, that are performed to verify that a design meets its specific requirements ***[AIAA S-122]***.

3.1.27 Development Tests

Tests conducted on representative articles to characterize engineering parameters, gather data, and validate the design approach ***[SMC-016]***.

3.1.28 Distribution Point

The distribution point is the location in the power distribution element where the power wiring branches to power two or more pieces of loads, not counting heaters ***[AIAA S-122]***.

Note: The source impedance of a distribution point is that measured "looking back" toward the main bus with the distribution point unloaded. It is the impedance at the main bus (including other loads) plus the wiring impedance to the distribution point and any capacitive loading added at the distribution point.

3.1.29 Double Insulation

Two independent insulating devices or layers of insulating material of sufficient thickness and durability to avoid damage due to electrical or mechanical stresses ***[AIAA S-122]***.

Note 1: Insulating layers are used in such a way that it would take failure of both devices or layers to result in a short circuit of the unfused power to ground or any other conductor.

Note 2: This technique is most often used to protect unfused power against shorts to ground or other conductors.

Note 3: Physical spacing sufficient to preclude sustained vacuum arcing may be considered as an independent insulator.

3.1.30 Electrical Power Subsystem (EPS)

Set of all equipment, wiring, and EPS-controlling software whose task is the generation, storage, control, and distribution of electrical energy to the input power terminals of the loads ***[AIAA S-122]***.

3.1.31 Energy Balance

Balance between energy generated or available and energy consumed or wasted over a defined orbital period ***[AIAA S-122]***.

3.1.32 Energy Reserve

Total amount of usable energy (in Wh), remaining in a battery that has been discharged to the maximum allowed DOD under normal operating conditions ***[AIAA S-122].***

Note: Energy reserve provides enough energy to ensure positive energy balance during the maximum sun-outage time when a loss of attitude control occurs coincident with the end of the longest eclipse. Energy reserve may also be used for other rare, deep discharges such as relocation with electric propulsion, or those that may occur in transfer orbit.

3.1.33 Energy Storage

Devices that store energy for use in powering the loads during periods (such as eclipse) when the output of the power generation element is insufficient to meet the overall load demand ***[AIAA S-122].***

Note: secondary (rechargeable) batteries are the prevalent means of energy storage, but ultracapacitors, flywheels, fuel cells, and primary (non-rechargeable) batteries also fall into this category.

3.1.34 Equivalent Level of Safety

An approximately equal level of safety; may involve a change to the level of expected risk that is not statistically or mathematically significant as determined by qualitative or quantitative risk analysis ***[AFSPCMAN 91-710, Volume 7]***.

3.1.35 Essential Loads

Loads that are essential for minimum controllability and commandability of the spacecraft ***[AIAA S-122]***.

Example: Examples of essential loads are command receivers, on-board computers, and critical heaters.

3.1.36 Fault Management

Process of detecting and reacting to the occurrence of a fault or anomaly, whether in hardware or software ***[AIAA S-122].***

3.1.37 First Cycle

The initial cycle following completion of all manufacturing processes ***[ST/SG/AC.10/11]***.

3.1.38 Fully Charged

A rechargeable cell or battery which has been electrically charged to its design rated capacity ***[ST/SG/AC.10/11]***.

3.1.39 Fully Discharged

A rechargeable cell or battery which has been electrically discharged to its endpoint voltage as specified by the manufacturer ***[ST/SG/AC.10/11]***.

3.1.40 Ground Support Equipment (GSE)

Non-flight items used in the ground testing of the EPS as integrated on the spacecraft, either at the contractor facility or at the launch site ***[AIAA S-122]***.

3.1.41 Gross Weight or Gross Mass

The weight of a packaging plus the weight of its content ***[49 CFR §171.8]***.

3.1.42 Hazard Class

The category of hazard assigned to a hazardous material under the definitional criteria of part 173 of this subchapter and the provisions of the § 172.101 table. A material may meet the defining criteria for more than one hazard class but is assigned to only one hazard class ***[49 CFR §171.8]***.

3.1.43 Hazardous Material

A substance or material that the Secretary of Transportation has determined is capable of posing an unreasonable risk to health, safety, and property when transported in commerce, and has designated as hazardous under section 5103 of Federal hazardous materials transportation law (49 U.S.C. 5103). The term includes hazardous substances, hazardous wastes, marine pollutants, elevated temperature materials, materials designated as hazardous in the Hazardous Materials Table (see 49 CFR 172.101), and materials that meet the defining criteria for hazard classes and divisions in part 173 of Subchapter C of this chapter ***[49 CFR §171.8]***.

3.1.44 Independent

Independent in safe mode vernacular usually refers to equipment not currently being used to support mission operations, prior to commanding safe mode.

3.1.45 Large cell

A cell in which the lithium content or lithium equivalent content of the anode, when fully charged, is more than 12 g ***[ST/SG/AC.10/11].***

3.1.46 Lithium Content

The mass of lithium in the anode of a lithium metal or lithium alloy cell. The lithium content of a battery equals the sum of the grams of lithium content contained in the component cells of the battery. For a lithium-ion cell see the definition for “equivalent lithium content” ***[49 CFR §171.8]***.

3.1.47 Lithium Equivalent Content

For a lithium-ion cell, the product of the rated capacity, in ampere-hours, of a lithium-ion cell times 0.3, with the result expressed in grams. The equivalent lithium content of a battery equals the sum of the grams of equivalent lithium content contained in the component cells of the battery ***[49 CFR §171.8]***.

3.1.48 Lithium-ion Cell or Battery

A rechargeable electrochemical cell or battery in which the positive and negative electrodes are both intercalation compounds (intercalated lithium exists in an ionic or quasi-atomic form with the lattice of the electrode material) constructed with no metallic lithium in either electrode. A lithium polymer cell or battery that uses lithium-ion chemistries, as described herein, is regulated as a lithium-ion cell or battery ***[ST/SG/AC.10/11]***.

3.1.49 Loads

Device or unit that uses electrical power provided by the EPS ***[AIAA S-122]***.

Note: Commonly called “loads” or “payload units.” Units and devices comprising the EPS components are themselves considered part of the loads in that they also consume power and are subject to EMC requirements in addition to their main purpose of steering electrical energy throughout the space vehicle. Battery recharge power is also considered part of the loads.

3.1.50 Losses

Distribution losses and energy storage system inefficiency losses associated with supporting the spacecraft electrical loads ***[AIAA S-122]***.

3.1.51 Main Bus

Main conductors to which the sources are attached prior to any branching ***[AIAA S-122]***.

Note: The impedance of this bus is common to all loads.

3.1.52 Maximum and Minimum Predicted Temperatures (MPT)

The maximum and minimum predicted temperatures are the highest and lowest temperatures that an item can experience during its service life, including all test and operational modes. The MPT are established by adding thermal uncertainty margins to the maximum and minimum model temperature predictions as defined in SMC-016.

3.1.53 Maximum Expected Operating Pressure (MEOP)

The Maximum Expected Operating Pressure (MEOP) is the maximum pressure that pressurized hardware is expected to experience during its service life, in association with its applicable operating environments ***[AIAA S-080]***.

3.1.54 Minimum Power Mode

Minimum Power Mode (MPM) is a minimum power state that would be invoked if entry into SHM fails to achieve a power safe operating state and the spacecraft batteries are approaching a state of complete discharge. The typical MPM response turns off all payload survival heaters and all remaining loads that are not required for attitude control and ground communications. MPM is intended to maximize the time for ground recovery to a safe power condition.

3.1.55 Mission Life

The contractually required period of time over which the spacecraft must meet all of its performance requirements ***[AIAA S-122]***.

Note: Mission life includes transfer orbit, orbit-raising, on-orbit, and de-orbit modes. EPS required life or an EPS component required life can be longer than the spacecraft mission life requirement. A design life can be longer than a required life.

3.1.56 Module or Battery Module

A battery module is an assembly of series-or parallel-connected (virtual) battery cells that are connected (usually in series) to form a partial or complete battery ***[SMC-017]***.

3.1.57 Normal Operation

Range of operational states of the space vehicle that exist or occur by design and in which the vehicle spends the vast majority of its time, according to the expectations of the mission designers and planners ***[AIAA S-1223.1.57 Operational States]***.

All foreseeable and intentional combinations of states, modes, or conditions within the EPS hardware and software ***[AIAA S-122]***.

3.1.58 Package or outside Package

A packaging plus its contents. For radioactive materials, see § 173.403 of this subchapter ***[49 CFR §171.8]***.

3.1.59 Packaging

A receptacle and any other components or materials necessary for the receptacle to perform its containment function in conformance with the minimum packing requirements of this subchapter. For radioactive materials packaging, see § 173.403 of this subchapter ***[49 CFR §171.8]***.

3.1.60 Packing Group

A grouping according to the degree of danger presented by hazardous materials. Packing Group I indicates great danger; Packing Group II, medium danger; Packing Group III, minor danger. See § 172.101(f) of this subchapter ***[49 CFR §171.8]***.

3.1.61 Payload

Self-contained instrument, sensor, or device that fulfills some mission objective ***[AIAA S-122]***.

3.1.62 Power Generation

All equipment involved in the generation of DC power for use by the loads and for charging the energy storage devices ***[AIAA S-122]***.

Note: Solar arrays are the most common technology for spacecraft power generation, other technologies, such as thermoelectric devices, fall into the category.

3.1.63 Power Margin

Difference between contingent source power and contingent load power ***[AIAA S-122]***.

Note: it is the margin between the lowest possible array output power and the highest possible load power.

3.1.64 Procurement Authority

The Procurement Authority is the agency responsible for spacecraft procurement ***[SMC-017]***.

3.1.65 Protoqualification Tests

Tests conducted to demonstrate satisfaction of design requirement using reduced amplitude and duration margins. This type of test is generally selected for designs that have limited production and supplemented with development and other tests and/or analysis to demonstrate margin. Protoqualification tests shall validate the planned acceptance program ***[SMC-016]***.

3.1.66 Prototype Lithium Batteries

A lithium cell or battery that has not completed the test requirements in Sub-section 38.3 of the UN Manual of Tests and Criteria ***[49 CFR §173.186]***.

3.1.67 Qualification Tests

Tests conducted to demonstrate satisfaction of design requirements including margin and product robustness for designs that have no demonstrated history. A full qualification validates the planned acceptance program, in-process stress screens, and retest environmental stresses resulting from failure and rework. Qualification hardware that is selected for use as flight hardware shall be evaluated and refurbished to show that the integrity of the hardware is preserved and that adequate margins remain to survive the rigors of launch and provide useful life on orbit ***[SMC-016]***.

3.1.68 Rated (or Nameplate) Battery Energy

The rated battery energy is the minimum guaranteed energy at beginning-of-life (BOL) for a defined range of mission charge control conditions, discharge load conditions, temperature profile, and minimum voltage requirement. The relationship that defines the rated battery energy is determined from the maximum power subsystem mission requirements and the real-time and accelerated-time database. Rated battery energy is less than, or equal to, the integral of the product of discharge current and voltage, where Id, a positive value, is the discharge current, and Vd, a positive value, is the discharge voltage. The limits of integration are from maximum allowable power subsystem charge voltage to either the minimum power subsystem battery voltage limit, or when the first cell reached lower cell voltage limit.

BOL is at the completion of battery-level qualification, proto-qualification, or acceptance test. Rated battery energy may differ from the vendor's cell ratings, but cannot be greater. Battery discharge may be accomplished with constant-current discharge; however, constant power discharge is the preferred method if it more closely simulated spacecraft power ***[SMC-017]***.

$$\text{Rated Battery Energy (Wh)} \leq \int I_d V_d \, dt$$

3.1.69 Regulated Buses

One whose voltage is controlled by means of a closed-loop negative feedback control scheme [***AIAA S-122]***.

Note: A sunlight-regulated bus is regulated during insolation and unregulated during eclipse.

3.1.70 Safe Mode

A temporary state of minimized satellite operations that is transitioned into as a result of an autonomously irreconcilable satellite fault or safety threat. This state discontinues mission payload operations; configures satellite assets for sufficient power collection and minimal power usage; maintains equipment health and command and telemetry communications with the satellite command and control segment; and yields fault/safety threat corrective action and operating state control authority to the satellite command and control segment.

3.1.71 Service Life

The service life of a battery, battery module, or battery cell starts at cell activation and continues through all subsequent fabrication, acceptance testing, handling, storage, transportation, testing preceding launch, launch, and mission operation ***[SMC-017]***.

3.1.72 Shelf-Life Limit

Shelf-life limit for a battery, module, or cell is the maximum allowed time from cell activation to launch. This includes any time in cold storage ***[SMC-017]***.

3.1.73 Single-point Failure

Single component, wiring, or connector failure, software glitch, or computer failure that results in the permanent loss of the spacecraft's ability to perform its primary mission for the intended design life span ***[AIAA S-122]***.

3.1.74 Small Battery

A battery composed of small cells, and in which the aggregate lithium content of all cell anodes, when fully charged, is not more than 500 g ***[ST/SG/AC.10/11]***.

3.1.75 Small Cell

A cell in which the lithium content of the anode, when fully charged, is not more than 12 g ***[ST/SG/AC.10/11]***.

3.1.76 Source Impedance

The source impedance (also called "driving point impedance") at any given point along a power distribution path is the small-signal ratio of the AC voltage phasor to the AC current phasor, as a function of frequency, across the power and return lines at that point. The measurement is made by breaking the positive side of the path at a desired measurement point and injecting a small AC current, then measuring the resultant voltage from positive to return, and then calculating the ratio of voltage to current, stepping over the desired frequency range as appropriate.

3.1.77 Special Permit

A document issued by the associate administrator, or other designated department official, under the authority of 49 U.S.C. 5117 permitting a person to perform a function that is not otherwise permitted under Subchapter A or C of this chapter, or other regulations issued under 49 U.S.C. 5101 et seq. (e.g., Federal Motor Carrier Safety routing requirements) ***[49 CFR §171.8]***.

3.1.78 Spike

Narrow impulse-like voltage waveforms that are produced by switching or fault-clearing events ***[AIAA S-122]***.

Note: Spikes are generally measured in terms of their volt-second impulse strength and peak voltage amplitude.

3.1.79 Survival Temperature

Survival temperatures are the cold and hot temperatures over which a unit is expected to survive, either operationally or non-operationally. The unit must demonstrate that it can be turned on at these temperatures and, although performance does not need to meet specification, the unit must not show any performance degradation when the environment or unit temperatures are returned to the operational or acceptance temperature range of the unit ***[SMC-017]***.

3.1.80 Test-Like-You-Fly

Test-Like-You-Fly is a pre-launch system engineering approach that examines all applicable mission characteristics and determines the fullest practical extent to which those characteristics can be applied in testing.

"All applicable mission characteristics" are concurrent attributes including, but not limited to, hardware and software configuration per mission phase or activity, external environments, internal induced environments, automated flight sequences, commanded operations, activity order and timing, up/downlinked telemetry, data product generation, signal services, mission planning, and end-user evaluation.

The “fullest practical extent” identifies the physical and engineering limitations, and balances what can be done in a flight-like manner with acceptable and understood risk and program constraints. The test article can be anything from a complex component, through all levels of integration, up to and including all space and operational software and systems involved in conducting the mission, but should ultimately be the final flight article ***[TOR-2010(8591)-6]***.

3.1.81 Thermoneutral Voltage

The thermoneutral potential or voltage of an electrochemical cell is the potential at which the cell charge or discharge process puts out zero heat, and thus is the potential corresponding to the enthalpy change of the charge/discharge reaction.

3.1.82 Transients

Bus voltage time-domain response due to an aperiodic event or due to a periodic low-frequency train of events ***[AIAA S-122]***.

3.1.83 Unregulated Buses

One whose voltage is approximately the same as the battery voltage, minus harness, and switching losses ***[AIAA S-122]***.

3.1.84 Virtual Cell

Group of cells wired in parallel ***[SMC-017]***.

3.2 Acronyms

A	Ampere
ADC(S)	Attitude Determination and Control (Subsystem)
Ah	Ampere-hour
AIAA	American Institute of Aeronautics and Astronautics
AFSPC	Air Force Space Command
AFSPCMAN	Air Force Space Command Manual
BDMS	Battery Disconnect and Maintenance System
C	Celsius
CBE	Cell Balance Electronics
CBU	Cell Bypass Unit
CFR	Code of Federal Regulation
CID	Current Interrupt Device
COTS	Commercial Off The Shelf
DBP	Depleted Battery Protection
DBR	Dead Bus Recovery
DC	Direct Current
DEC	Di-Ethyl Carbonate
DMC	Di-methyl Carbonate
DoD	Department of Defense
DOD	Depth of Discharge

DOT	Department of Transportation
EC	Ethylene Carbonate
EGSE	Electrical Ground Support Equipment
ELV	Expendable Launch Vehicle
EMC	Ethyl Methyl Carbonate
EOCV	End-of-Charge Voltage
EPC	Electronic Power Converters
EPDS	Electrical Power Distribution System
EPS	Electrical Power Systems
ER	Eastern Range
FMS	Fault Management Software
FOD	Foreign Object Debris
GEO	Geosynchronous Earth Orbit
kWh	Kilo watt-hour
LEO	Low Earth Orbit
Li-CoO_2	Lithium Cobalt Dioxide
Li-Ion	Lithium Ion
Li-NCA	Lithium Nickel-Cobalt-Aluminum Oxide
MCMB	Mesophase Carbon Micro Beads
NASA	National Aeronautical & Space Administration
Ni-Cd	Nickel Cadmium
Ni-H2	Nickel Hydrogen
PD	Power Distribution
PMAD	Power Management and Distribution
PTC	Positive Temperature Coefficient
PVdF	Ployvinylenedifluoride
SEI	Solid Electrolyte Interface
SOC	State-of-Charge
TLYF	Test Like You Fly
TOR	Technical Operating Report
UL	Underwriters Laboratories
UN	United Nations
V	Volts
WR	Western Range
Wh/kg	Watt-hours per kilogram

4. Power Subsystem Overview

The Electrical Power Subsystem (EPS), also sometimes called the Electrical Power and Distribution Subsystem (EPDS), is a critical spacecraft subsystem. As almost all spacecraft equipment needs electricity for operation, failure of the EPS equals failure of the mission. Proper design of the EPS ensures reliable delivery of electrical power to payloads, bus equipment, heaters, and to rechargeable batteries. Robust operation of the EPS is ensured through fault-tolerant design principles, including redundant electronics, double insulation of primary (unfused) bus power, prevention of plasma arcing, limiting of bus voltage transients, and so forth. The industry standard AIAA S-122-2007, "Electrical Power Systems for Unmanned Spacecraft," contains what are considered the best practices for ensuring a reliable EPS design.

Any EPS can be divided into four functional areas – Power Generation (or Energy Conversion), Energy Storage, Power Management (PM), and Power Distribution (PD). Often, the latter two are combined into the term Power Management and Distribution (PMAD).

For most earth-orbiting spacecraft, solar arrays are used to convert solar irradiance into electrical power. To allow spacecraft operation during eclipse periods or at times when the power demand by loads is greater than the available power from the solar arrays, batteries are used for energy storage. PMAD, which generally includes both hardware and software components, steers electrical power from the solar arrays to the loads and to the batteries, and also from the batteries to the loads, as needed to maintain proper energy balance, that is, to keep the bus voltage within acceptable bounds to ensure proper operability of user equipment.

The basic principles of EPS operation have changed very little over the course of the Space Age. Of course, the technologies of solar cells, batteries, and electronics have advanced enormously, with the result that modern EPS equipment has lower mass, higher specific energy(W/kg), and higher efficiencies than earlier systems.

One important advance in energy storage has been the advent of lithium ion (Li-Ion) batteries that are suitable for long-duration space missions. With energy densities two or three times as great as Nickel Hydrogen (Ni-H2) batteries, the use of Li-Ion promises tremendous mass savings for today's space systems. The long road to qualification of Li-Ion batteries for high-reliability space has been fraught with challenges in the areas of cell chemistry, the design and construction of cells, and in life testing.

This document provides an overview of Li-Ion batteries and how to successfully use them in EPS designs. Li-Ion requires different approaches to charge management and protection of batteries than did Nickel Hydrogen. Cell balancing techniques often must be used to prevent divergence of cell voltages within a battery. Batteries must be protected against inadvertent overcharge, as well as inadvertent over-discharge, which has happened often enough and in different ways on some past missions to be considered a realistic threat, despite the best efforts of Fault Management designs and Failure Modes and Effects Analysis. Lastly, safety regulations and design approaches to ensure safety are discussed at length.

The following Table provides an overview of the technical content contained within this document.

Section No.	Title	Content
5	Power Subsystem Architecture	a) Defines various aspects of a power subsystem: energy generation, energy storage, power management, power distribution. b) Provides four different power subsystem configurations with diagrams.
6	Li-Ion Battery Sizing	a) How to optimize battery size while considering capacity loss due to internal pack losses, cell voltage divergence, redundancy, cell aging and temperature effects. b) Additional capacity required for anomaly resolution. c) Sizing needs to consider completion of life test and uncertainty in prediction of EOL performance.
7	Li-Ion Cell and Battery Design	a) Overview of two key Li-Ion chemistries describing key design, construction and performance characteristics and limitations. b) Overview of Li-Ion battery designs: cell configuration, mechanical design, thermal configuration and analysis.
8	Li-Ion Charge Management Methods	a) Describes how Li-Ion differ from Ni-H2. b) Provides specific charge methods used for Li-Ion. c) Impact of cell resistance on charging, especially for LEO orbits. d) Impact of parasitic and ripple currents.
9	Overcharge Protection	a) Describes consequences of overcharge. b) Overcharge protection consists of cell voltage monitoring, response to overcharge, backup overcharge protection scheme.
10	Cell Balance Electronics	a) Feasible for specific types of battery cell configurations. b) Describes the shunt, continuous energy transfer, and individual cell charger balancing schemes. c) Addresses unequal parasitic loads across cells. d) Considers S/C integration with live battery.
11	Cell Bypass	a) Provides alternate current path around an open, short, or high resistance cell. b) Multiple designs, but one design preferred for Li-Ion. c) Autonomous vs manual activation.
12	Depleted Battery Prevention and Maintenance	a) Provides safe mode scenario and how to prevent battery over-discharge. b) Discusses disconnect switch considerations for regulated and unregulated designs. c) Need capability to heat and charge battery while disconnected.

Section No.	Title	Content
		d) Need for autonomous or manual battery reconnect. e) Hardware reliability considerations.
13	Fault Recovery Considerations	a) S/C level recovery consideration (temperature, attitude, and ground contact). b) Provides steps for full vehicle recovery. c) On-orbit lessons learned from dead bus events.
14	Design and Workmanship Verification	a) Highlights standard development, qual, acceptance and life cycle tests. b) Provides specialized test considerations for Li-Ion: cold temperature tests, validation of each cell balance circuit prior to launch, bypass switches and battery disconnect and maintenance hardware at unit, system and S/C level.
15	Class A, B, C, D Missions	a) Gives characteristics of different mission classes. b) Standard design practices to insure robust power subsystem design.
16	Safety	a) Safety considerations, guidelines and best practices for Li-Ion batteries. b) System safety process flow chart. c) Li-Ion battery risks. d) Safety requirement guidelines (Range Safety, NASA & DOT). e) Li-Ion safety features for cell, battery power subsystem and EGSE. f) Required safety tests for Range Safety, DOT and UN. g) Operational consideration for manufacturing, S/C integration, handling and transportation, launch site processing and operations. h) Safety compliance certification.

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5. Power Subsystem Architectures

All active spacecraft systems and components require electrical power. This is provided by a direct current (DC) EPS. Primary electrical power is provided to the loads by a moderate to high voltage bus, with secondary power within the loads provided by "point-of-load" electronic power converters (EPCs). This section will focus on the various architectures for the primary power buses, with additional emphasis on those features that are particular to the inclusion of Li-Ion batteries.

Each of the architectures uses a collection of the various building blocks described below in order to make up the complete power system.

Power Generation

Power for operating spacecraft loads and replenishing energy storage devices can be produced by various means, with the method used depending on total power requirements, mission orbit, and mission duration.

The primary method of power generation for the majority of spacecraft is solar photovoltaic, which employs a solar array. The solar array consists of individual solar cells connected in series and parallel, with the exact number and arrangement defined by the total current and voltage required over all mission phases. The solar array can be either body mounted or connected to one or more booms extending out from the main spacecraft body. The body mounted solar array may have the solar cells attached directly to the spacecraft structure or mounted to rigid panels attached to the spacecraft body. For a boom mounted array, the cells are mounted to panels which are in turn connected to the boom. These panels can either be rigid, as in most applications, or retractable, as on the International Space Station. The boom mounted array will usually be gimbaled, in order to allow the arrays to be controlled to track the sun. In these instances, slip rings are employed to pass the solar array current from the rotating boom(s) to the spacecraft primary power bus.

Other methods of power generation include solar thermal and nuclear energy conversion. Since these are not widely used, nor do they utilize batteries, they will not be discussed further.

Energy Storage

Most spacecraft utilize secondary/rechargeable batteries for energy storage. The batteries are used to provide the required power during eclipse periods, as well as to provide supplemental power when solar array power is insufficient during short term operations such as maneuvering. Over time, the most common types of batteries used have been nickel cadmium (Ni-Cd), transitioning to Ni-H2 and more recently moving to Li-Ion. One of the primary reasons for this move to the different technologies over the years has been weight savings. Any launch vehicle has a maximum payload that it can lift into orbit, so reducing weight in order to use the smallest practical launch vehicle possible is paramount, since increased lift capability equates to increased cost. In addition, for a given launch vehicle, there is a relationship between the mass of the payload and the launch cost, often referred to as "dollars per kilogram". Reducing the mass of support components on a spacecraft can also allow for having increased payload on the satellite for the same total mass, such as more transponders on a communications satellite.

Each succeeding advance in battery cell technology has led to a reduced battery mass for a given amount of energy storage capability. In terms of cell specific energy, as measured in watt-hours per kilogram (Wh/kg), the three technologies compare as follows: Ni-Cd 40-50, Ni-H2 50-60, Li-Ion 100-150. While Ni-H_2 offered approximately a 25% mass savings over Ni-Cd, Li-Ion has at least a two to one mass savings over Ni-H2, justifying working within its unique operating and handling constraints.

Another comparison between the various cell types is charge/discharge efficiency, which is the amount of power discharged by the battery divided by the amount of power delivered to the battery, where the difference accounts for the energy lost as heat in the battery. While this does not directly reduce battery mass, it can impact the solar array sizing, since the lost energy has to be provided during the charging cycles. The three technologies compare as follows: Ni-Cd 70-90%, Ni-H2 85%, Li-Ion up to 95%.

Another method for energy storage is fuel cells. For a mission of any meaningful length, regenerative fuel cells are required, which can require a substantial amount of energy for regeneration during periods of sunlight operation. Since these are not batteries, in the strictest sense, they will not be discussed further.

Power Management

Solar Array Controller: A solar array controller is used to control the amount of current that is passed from each solar array circuit to either the batteries or the main bus (series connection) or controlled with a peak power tracker. The solar array controller also includes any necessary conditioning circuitry for controlling current ripple to within required levels.

Battery Charge: During periods where the amount of available solar array energy exceeds spacecraft load requirements, the battery charger will provide battery charging control. By comparing the actual battery charge current to a reference representing the required charge current, the charger will increase/decrease the supplied current, in order to maintain the desired level. Battery voltage is monitored to control tapering back of the charge current as the battery approaches full charge as well as to terminate charge to prevent overcharging.

Battery Discharger: When the spacecraft is in eclipse, or when available solar array energy is insufficient to meet spacecraft load requirements, the battery discharger will control the drawing of energy from the batteries to supply it to the spacecraft bus. Comparing the actual bus voltage to a reference representing the desired voltage, the discharger will control the amount of current drawn from the batteries in order to maintain the desired voltage.

Cell Balancing Electronics (CBE): In order to prevent either overcharge or over-discharge of individual Li-Ion battery cells, it is important to equalize the cell voltage or state-of-charge (SOC) within its design limits. This is accomplished by cell balancing, using cell balancing electronics (CBE) connected across the battery cell modules. Additional details on cell balancing, and implementations of CBE, can be found in Section 10.

Depleted Battery Protection (DBP)

During fault conditions, where there is not enough solar array energy available to maintain acceptable levels of battery charge, it is possible for the cells to become over-discharged. This is not an issue for Ni-Cd or Ni-H2 cells, but is a concern for Li-Ion cells. For most Li-Ion chemistries, discharge below a certain voltage can lead to irreversible damage (refer to Section 7.1.8). In order to provide DBP, a means of disabling or blocking additional battery discharge may be implemented for use in the event of a failed safe mode response (refer to Section 12.1.3). This can be implemented with a stand-alone unit, or integrated within the battery charger and battery discharger. In either case, the key requirement is to achieve as small a parasitic load on the batteries as possible.

Power Distribution (PD)

Power distribution is how the EPS provides power from the main power bus to the using loads. It consists of not only the harnessing between the bus and the loads, but also any required fault protection, such as fuses, circuit breakers, or other current limiting devices. It may also include On/Off switching for those loads that do not provide that capability themselves.

NOTE: Additional details on Power Subsystems Architectures can be found in the following in AIAA S-122 and Reference 1.

5.1 Unregulated Bus

Since Li-Ion batteries are normally composed of well matched cells, they can be operated in parallel for both charging and discharging. In order to maintain this matching, cell balancing electronics (CBE) are required in order to keep the individual cells at the same voltage. Figure 5-1 shows an unregulated bus implementation with multiple parallel batteries. During periods of insolation, the solar array controller passes solar array current to the bus, setting the level to an amount that satisfies the load requirements while also providing charge current to the batteries. The charge current in each of the batteries is monitored and fed back to the solar array controller to prevent excessive charge currents in the batteries, as well as to taper back the current as the batteries become fully charged. If the solar array controller uses a series connection to the bus, a bootstrap supply must be provided to supply power for turning on the switches when insolation returns after a depleted battery condition to allow power to get to the bus. This configuration IS NOT SUITABLE for use with NiH2 batteries, due to the wider variation in cell voltage as compared to a Li-Ion battery with CBE.

The battery implementation must take into consideration the loss of a cell. This is due to the effective voltage of the battery experiencing the cell loss dropping by the operating voltage of that cell, and the battery not being able to be utilized unless the voltage of the other battery (or batteries) is in the same range. This is most pronounced when using Li-Ion batteries, since the voltage loss is on the order of 3.5V to 4V. If a means is provided for bypassing the failed cell, the loss of the failed cell can then be compensated for. Among the methods that can be used to accommodate the loss of a cell are: removing a cell from the other battery (or batteries), adding a replacement cell to the battery experiencing the failure, or having a system that is N+1 redundant at the battery level with the battery having the failed cell completely disconnected from the bus. For the option utilizing a replacement cell, a means must be provided to maintain that cell so that it is viable should it be needed. An alternative method of providing a replacement cell is to include a pseudo-cell in series with each battery, as shown in the inset of Figure 5-1. The pseudo-cell does not store energy, but is a bi-directional electronic power converter (EPC) that can emulate a battery cell by sourcing or sinking current. Until required to operate, the pseudo-cell is bypassed by a mechanical relay. Once enabled, the pseudo-cell is programmed to match the average voltage of the remaining cells in the affected battery.

After a depleted battery condition, recovery of spacecraft systems will not be possible until the batteries can be brought to a voltage high enough to exceed the undervoltage lockout threshold of the hardware involved. The battery can be recharged by either utilizing the normal charging method, or with additional hardware to accomplish this. In the case where a means has been provided to disable battery discharge, this should be accomplished prior to re-enabling discharge. Extreme care must be exercised, especially when using the normal charging method. The ability of Li-Ion cells to accept charge is greatly reduced at cold temperatures. If a charge rate that exceeds what the cells can accept is programmed, the bus voltage will not be clamped by the battery, and the bus will move towards the

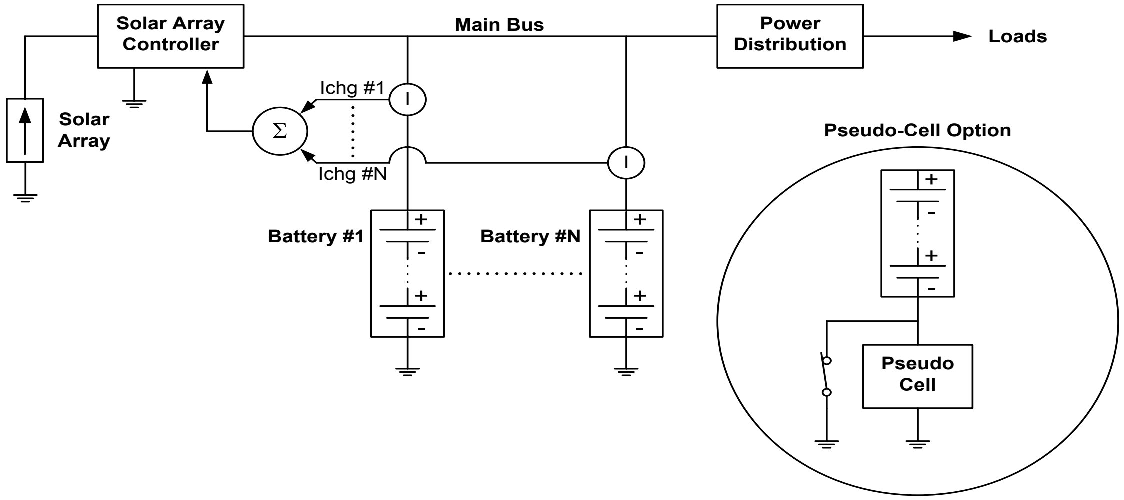

Figure 5-1. Unregulated bus.

open circuit voltage of the solar array, which can damage downstream components. For example, on a 28V battery dominated bus, components are normally designed to accept short duration transients of up to 40V, whereas the open circuit voltage of the solar array will normally be in excess of 56V. For the shunted solar array switch case, a means must be provided to power either the normal charging electronics, or any auxiliary means, as the battery is not guaranteed to be in a state that can support even minimal operations.

5.2 Battery Dominated Bus

In a battery dominated bus, the bus voltage is equal to the battery voltage. During periods of insolation, the solar array controller controls the passing of solar array current to the bus, setting the level to an amount that satisfies both the load requirements and desired charge current. Figure 5-2 shows an implementation of a battery dominated bus with multiple batteries. A single battery configuration would be similar to a single battery unregulated bus. In the multiple battery case, the individual batteries are connected to the main power bus with a diode, allowing for individual control of battery charging as well as accommodating mismatches in battery voltage, which allows this implementation to work with both NiH2 and Li-Ion batteries. In this configuration, the solar array circuits are normally cross-strapped to the solar array controller for multiple batteries. This enables the solar array size to be minimized. By cross-strapping, the entire solar array current is always available to the bus. In the absence of cross-strapping, the solar array would have to be sized so that any battery bus could provide the full required load current. This is because, in cases where the battery voltages are not equal, the current from the lower voltage battery is prevented from reaching the bus, due to the blocking diode being reverse biased.

The same provisions for loss of a battery cell as those required for an unregulated bus must be taken into consideration for the battery dominated bus. For Li-Ion batteries, the advantages of the added complexity of individual charge control should be weighed against the simplified approach afforded by the unregulated bus.

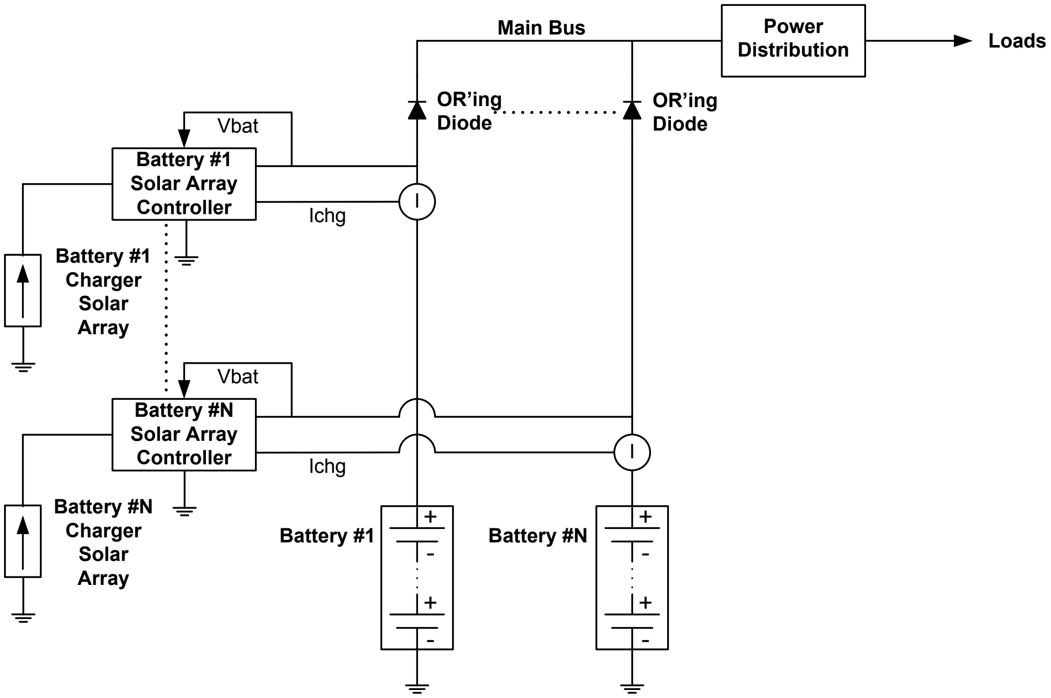

Figure 5-2. Battery dominated bus.

All of the constraints for a depleted battery recovery for an unregulated bus battery system apply. Overall system recovery may be possible once the first battery is back online, however, a trade may be required to determine how much of the available energy will be dedicated to recovery of the remaining battery (or batteries) to support eclipse operation and how much will be dedicated to recovery of other systems once the first battery is back online.

5.3 Sunlight Regulated Bus

In a sunlight regulated bus, the solar array circuits are connected to the bus by the main bus solar array controller, as shown in Figure 5-3. The bus voltage is maintained at a predetermined level by comparing the actual bus voltage to a reference voltage representing the desired level. The bus voltage will still be a function of the battery voltage during periods of eclipse, or when insolation is insufficient to meet the required current. The batteries are connected to the main power bus by a blocking diode for discharge and each has a battery solar array controller for charge control. An alternative approach has the power for battery charging drawn directly from the bus, rather than the solar array.

The sunlight regulated bus has the advantage of providing power during recovery via normal means, once the bus is initially brought online, as compared to the additional measures required for a battery dominated bus. It also alleviates the concern for overvoltaging the bus, since the voltage is actively regulated, and not dependent on the battery voltage. System recovery may also commence as soon as the bus is at a voltage that can support the required loads, however, a trade may still be required to determine how much of the available energy should be dedicated to overall recovery of the vehicle and how much should be allocated to recovering the operation of the batteries. A series switched main bus solar array controller would need a bootstrap supply for depleted battery recovery.

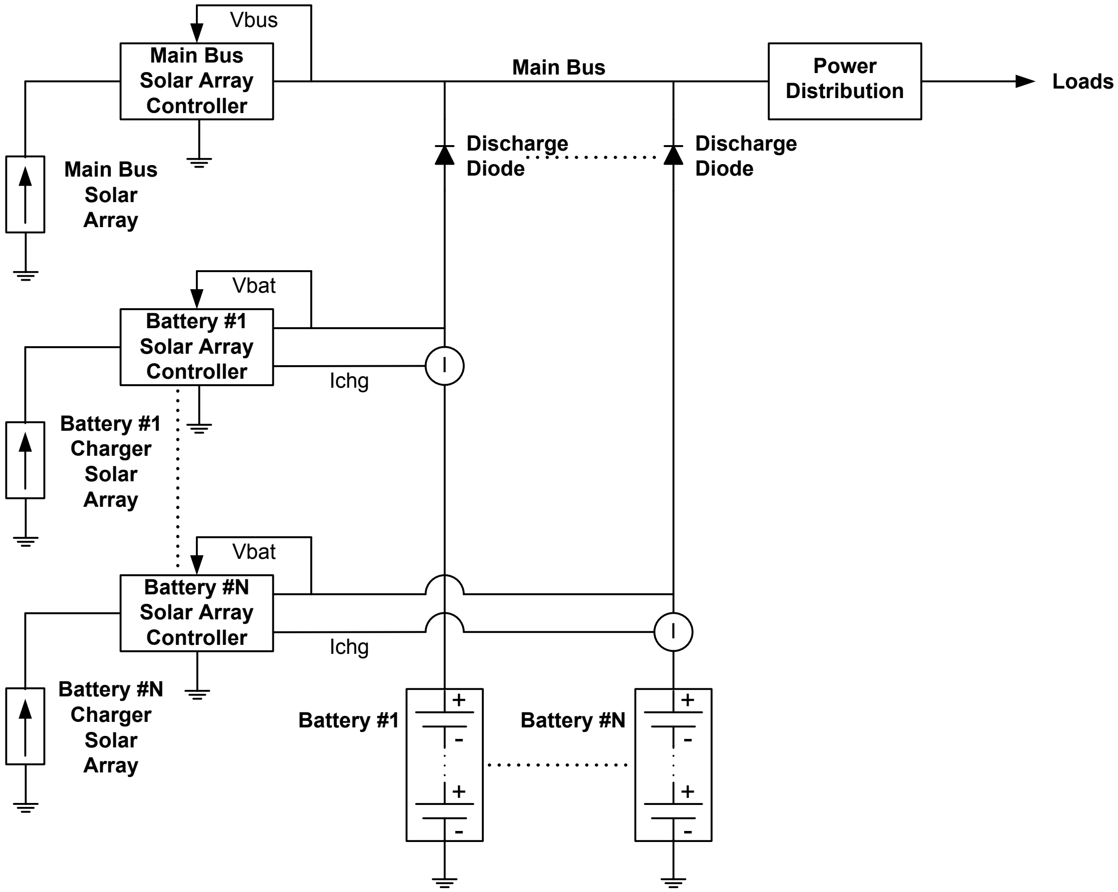

Figure 5-3. Sunlight regulated bus.

Once again, accommodations must be made for loss of a battery cell. For Li-Ion batteries, the advantages of the added complexity of a sunlight regulated bus should be weighed against the simplified approach afforded by the unregulated bus.

5.4 Fully Regulated Bus

The fully regulated bus is similar to the sunlight regulated bus. The primary difference is that the blocking diode between the battery and the bus for conducting current during discharge is replaced by a battery discharger. Figure 5-4 shows a fully regulated bus implementation. As with the other bus types, a bootstrap supply would be required for depleted battery recovery for a series solar array controller.

As with the sunlight regulated bus, system recovery may commence as soon as the bus is at a voltage that can support the required loads, however, a trade may still be required to determine how much of the available energy should be dedicated to overall recovery of the vehicle and how much should be allocated to recovering the operation of the batteries.

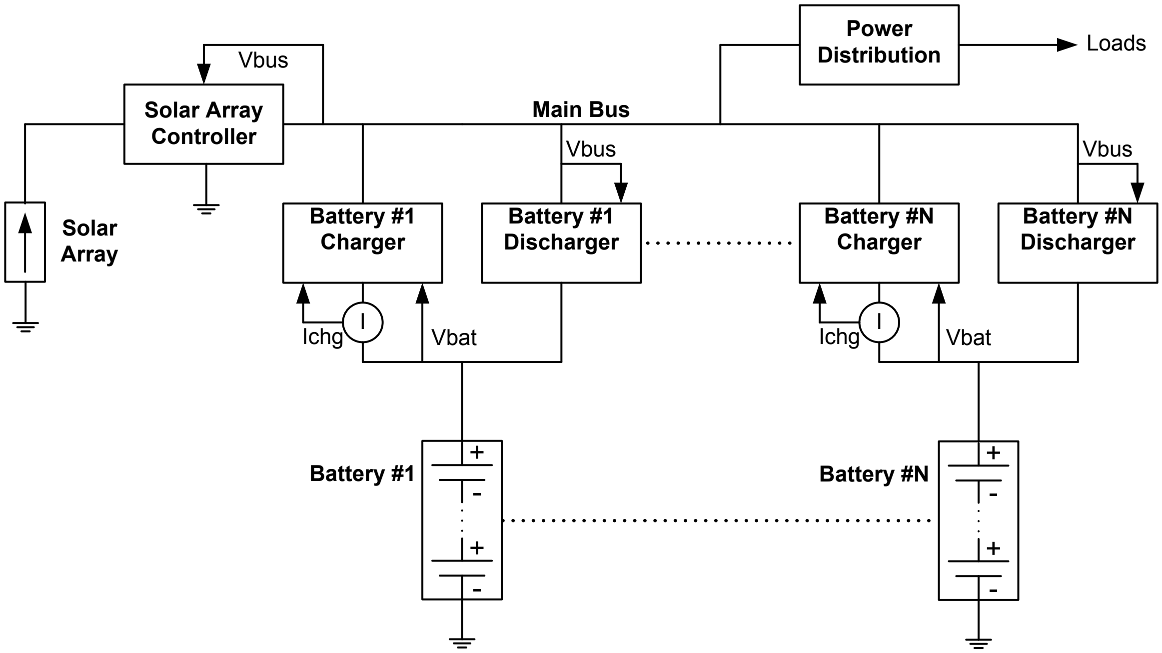

Figure 5-4. Fully regulated bus.

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6. Li-Ion Battery Sizing

Battery sizing refers to the science of designing the optimal quantity of battery cells such that the battery or batteries provides the required energy and peak power demands, while operating within a desirable range of operating voltages over the life of the mission. In addition to the quantity of cells, battery sizing includes selection of the optimal combination of series and parallel cells based on available space cell capacity sizes. When sizing the battery one must also take into consideration capacity loss due to internal pack losses, cell voltage divergence, redundancy, capacity loss due to ageing effects. Also, the battery must be sized to store sufficient energy to operate through program specified anomaly conditions.

6.1 Battery Energy, Battery Voltage, and Peak Pulse Power

The battery must be sized such that it can provide the required power through the longest expected usage period. For most spacecraft, this is the earth eclipse period. To the first order, the battery is sized based on the known or expected energy capacity of the individual Li-Ion cells, and knowledge of the maximum energy demand. This calculation estimates the minimum number of battery cells. The cells must then be combined to form one or more batteries.

The number of cells, or virtual cells, connected in series determines the battery voltage. Battery voltage is important from both a battery life consideration and a system design standpoint. When used in battery dominated bus architecture, the battery voltage becomes the bus voltage. The battery voltage must be designed to operate within the range of the power users. Also, the maximum usable solar array power may be determined by the battery voltage. In the case of the battery dominated bus architecture, the number of series connected cells is determined primarily by the operating range of the user equipment with consideration of a compatible solar array design.

Fully regulated bus systems usually use a boost converter to transfer energy from the battery to the bus. The boost converter may tolerate a wide range of battery input voltages, but its performance may be optimized for higher rather than lower input voltages. In this case, it is desirable from a conversion efficiency standpoint to configure the required battery cells into a high voltage configuration.

The fully regulated bus architecture relies on the boost converters to deliver battery power to the bus. Depending on the design of the boost converter, it may be more capable of delivering higher peak bus power when operating from a higher battery input voltage. This too may be a consideration when determining the optimal series-parallel cell configuration.

6.2 Capacity Loss Due to Internal Pack Losses

Packaging N cells into a battery does not guarantee that the battery will deliver N times the energy of a single cell. In addition to the cell's internal I^2R loss, power is lost in the conductors between cells. Good design practice dictates that electrical connections between cells in a virtual cell, and connections between virtual cells have a low resistance. Still, there will be a non-zero resistance between the virtual cells and between the virtual cells and the battery terminals. This resistance acts to reduce battery capacity.

Capacity is usually defined by discharging a cell, or battery, from a known voltage at a constant rate until the cell or battery voltage reaches a threshold value. Battery capacity is defined as the integral of time and current or power during the discharge region. The interconnect resistance in series with the cells will cause the battery voltage to reach the voltage threshold earlier than it would have without the additional resistance. This results in a lower measured capacity. Although the battery cells may produce 10 kWh, the battery may only provide 9.7 kWh as measured at its external terminals. The difference in energy shows up in the form of heat generated inside the pack. These I^2R losses may be a significant factor in the battery thermal analysis.

6.3 Capacity Loss due to Cell Voltage Divergence

The degree to which cells (or virtual cells) can be balanced has an effect on battery capacity. Li-Ion cells are normally charged to a precise end of charge voltage. This voltage threshold is usually defined by the cell supplier and is verified by life test. In order for each cell in the battery to meet its guaranteed operational life, it should not be charged higher than the established end of charge. When charging the battery, the battery should be charged such that the voltage of the highest cell does not exceed the predefined end of charge voltage. If the cell voltages are not balanced, the remaining cells in the battery will be charged less than the cell that reached the end of charge voltage first. This condition results in a lower total battery voltage.

For the battery dominated bus architecture, this means the bus voltage will be less than it would otherwise and could result in lower solar array power. During discharge, the lower voltage battery must deliver higher current to meet the same constant power loads. For the fully regulated bus, the boost converters compensate for lower battery voltage by discharging at higher current. In both cases, the lower battery voltage will result in higher current which may result in a depth-of-discharge (DOD) that exceeds the battery qualification conditions.

6.4 Capacity Loss Due to Loss of Redundancy

Highly reliable spacecraft always employ some degree of redundancy in the battery design. Even Class C and D missions may employ battery redundancy schemes if they are used in applications where the spacecraft must have limited functionality in the event of single failures. The redundancy scheme must consider the effects of internal cell shorts, cell opens, cell case to ground shorts, cell to cell shorts. Not all failures are survivable, but they must be mitigated through battery design.

Loss of redundancy should be considered when evaluating spacecraft performance. A reliable spacecraft must be able to meet its mission requirements with the specified number of cell failures. The system analyst must consider the operating conditions of the batteries and/or virtual cells that remain after the prescribed number of failures has occurred. The remaining batteries and/or virtual cells should still be operated within the battery's allowable design limit.

The loss of battery redundancy may result in higher operating currents for the remaining cells. Battery voltage, DOD, and thermal analyses should verify that the design meets requirements under these conditions.

6.5 Capacity Loss Due to Ageing and Temperature

Li-Ion batteries degrade over life. Capacity is lost both in terms of inherent capacity loss, and apparent capacity loss due to increased internal resistance. The most noticeable change is the increase in cell impedance. Increased resistance results in lower battery voltage during discharge. Given the same constant current discharge rates, the aged battery will deliver less energy for the same ampere-hour discharge compared to the same battery with no ageing. This is an "apparent capacity loss" because most of the lost capacity is still available at lower discharge rates.

When operated with constant power loads, the lower battery voltage during eclipse discharge results in higher battery current. The higher battery current, in turn, results in even lower battery voltage due to IR losses within the battery. The system analysis must include the effects of the worst case increase in cell resistance.

Similarly, Li-Ion cell capacity and impedance performance will decline as operating temperature decrease. Section 7.1.6 quantifies the effect of temperature and impedance across a nominal operating region for common Li-Ion cells. It can be noted that the difference in cell impedance can increase by a factor of 1.5 or more as the cell operating temperature reduces from 20 deg C to 10 deg C. When operating at low temperatures, one must consider these performance impacts in the system analysis. This is particularly critical when assessing the effects of high pulse current on battery voltage.

6.6 Battery Sizing for Anomaly Resolution

In addition to sizing for nominal and peak battery power demands, the system designer must consider the need for battery energy for spacecraft anomaly resolution. That is, the spacecraft may have a safe mode response which is initiated by loss of attitude information.

The anomaly recovery may cause the battery to discharge well beyond its normal eclipse limits. Most battery designs are limited to operating such that at the end of the longest eclipse the remaining high rate energy is 25% or more of the total battery capacity for geosynchronous earth orbit (GEO) spacecraft, and 60% or more for low earth orbit (LEO) spacecraft. The safe mode response may include some form of load shedding, which reduces the power demand on the battery. By operating at a lower discharge rate the Li-Ion battery is capable of delivering more energy than at high rate. Nevertheless, the battery should contain sufficient high rate and low rate energy to operate through the expected safe mode recovery sequence.

Along with increased resistance the Li-Ion battery also loses real capacity as the cells age. During normal operations this may not be apparent because the battery never operates at very low state-of-charge (SOC). However, this loss of real capacity may have an effect on anomaly recovery because the battery may be required to operate at very low SOC. Capacity loss should be determined by life testing.

6.7 Cell and Battery Testing Related to Battery Sizing

Knowledge of battery capacity, voltage profiles, and internal resistance are fundamental to determining the battery performance. These quantities can be determined directly from measurements in laboratory tests. Determining cell characteristics at end-of-life is not possible without extensive life testing. There are on-going efforts to predict battery capacity loss and resistance growth through the use of detailed cell models. However, even the most complex models require validation through correlation of model predictions to long term cell testing results.

Li-Ion battery capacity loss is directly related to its operating voltage, temperature, calendar age, number of discharge cycles, and the DOD of those cycles. A battery operated in a LEO environment at LEO discharge and charge rates will age differently than the same battery used in a GEO application. Ideally, the battery life test should duplicate the discharge and charge profiles expected on orbit.

Life testing is required to determine or estimate the end-of-life battery characteristics. The EOL battery characteristics must be used when performing the battery sizing process described in this section.

In order to guarantee that the battery will perform as expected, the battery must be operated such that its voltage, temperature, and DOD do not exceed the conditions used for the life test.

6.8 Battery Sizing and Margin

Li-Ion batteries are relatively new products. The nature of the chemistry does not allow for rapid determination of end-of-life characteristics, especially when the expected range of operation is 10 or more years. Ground battery storage and integration may add another 2 to 5 years of degradation prior to launch. Furthermore, Li-Ion cell technology is changing as cell materials and manufacturing processes change. Even with no change in materials or chemistry, cell capacities and internal resistance may vary from one manufacturing lot to another.

These factors combine to introduce uncertainty about capacity loss and resistance growth predicted at end-of-life. Prudent engineering practice is to design such that the battery meets all requirements with reasonable worst case estimates for capacity loss and resistance growth and operating temperature.

Furthermore, a complete program risk assessment should include the uncertainty in predicting future Li-Ion battery characteristics.

7. Li-Ion Cell and Battery Design

7.1 Li-Ion Cells

Li-Ion battery technology is now the preferred technology for most military space applications. Their designs provide higher energy density, higher specific energy, reduced self discharge rates and reduced cell thermal dissipation in contrast with nickel hydrogen technology. This can result in approximately a 50% reduction in battery weight and 75% reduction in volume. However, Li-Ion is generally not tolerant to overcharge or over-discharge, and as such, requires specific electronic hardware to protect the battery. One remaining risk for Li-Ion technology is demonstration of full operational life for missions of 10 – 16 years.

Li-Ion charging and discharging occurs through the migration of Li-Ions in the electrolyte solution between the anode and cathode electrodes. Specifically during charge lithium ions migrate from the cathode layers and intercalate into the anode. On discharge the ions migrate from the anode and intercalate into the cathode. Ideally, since lithium ions intercalate into the electrode material the cell contains no free lithium metal. There are a wide variety of candidate cathode and anode materials that facilitate the reversible intercalation process over many cycles. Key material properties such as capacity per unit volume, charge/discharge efficiency and output voltage are important characteristics of the selected material to insure high energy density and specific energy. As a result there are many different Li-Ion chemistries that are collectively described as a Li-Ion cell. Each of these chemistries has their own specific operating voltage, preferred temperature range, energy density, specific energy, thermal dissipation, and safety characteristics.

At present the two most common Li-Ion chemistries for military space include lithium cobalt dioxide ($Li\text{-}CoO_2$) and lithium nickel-cobalt-aluminum oxide (Li-NCA). It is anticipated that other chemistries will become available in the future that will satisfy the 10 – 16 years missions for military satellites.

The general electrochemical reaction for $Li\text{-}CoO_2$ cell is as follows:

$$\begin{array}{rcll} \mathrm{LiCoO_2} & \xrightleftharpoons[\text{discharge}]{\text{charge}} & \mathrm{Li_{1-x}CoO_2 + xLi + xe^-} & \text{(Cathode)} \\ \mathrm{C + xLi^+ + xe^-} & & \mathrm{Li_xC} & \text{(Anode)} \end{array}$$

The general electrochemical reaction for the typical space Li-NCA cell is as follows:

$$\begin{array}{rcll} \mathrm{Li(NiCoAl)O_2} & \xrightleftharpoons[\text{discharge}]{\text{charge}} & \mathrm{Li_{1-x}NiCo\,AlO_2 + xLi + xe^-} & \text{(Cathode)} \\ \mathrm{C + xLi^+ + xe^-} & & \mathrm{Li_xC} & \text{(Anode)} \end{array}$$

7.1.1 Cathode Electrode

The cathode electrode consists of a thin coating of active material on one or both sides of an aluminum current collector. The coating is a mixture of the active powder mixed with other conductive carbon materials and binders. The polyvinylenedifluoride (PVdF) polymer binder is commonly used to hold the electrode structure together and bond it to the current collector. The binder helps to accommodate volumetric changes of the electrode during the charge-discharge cycle. The current collector is a thin metal foil which transfers current evenly throughout the cell to the active material as well as providing mechanical support for both the active material and electrical leads that are connected to the cell terminals. Performance of cathode electrodes will vary based on porosity, particle size, purity, additives, and mixture ratios. Uniformity of electrode manufacturing is key to preventing formation of lithium plating on the anode, a premature cell failure mechanism. One common cathode material used in long life space satellites is lithium cobalt dioxide (Li-CoO_2). Li-CoO_2 was one of the first Li-Ion chemistries to be successfully marketed in commercial applications. Another common space cathode material is lithium nickel-cobalt-aluminum oxide (Li(NiCoAl)O2) often abbreviated as NCA. This material has wide commercial and military use.

7.1.2 Anode Electrode

The anode electrode consists predominately of graphite powder, polymer binder (such as PVdF), and a metal current collector (typically copper or titanium foil). The anode typically contains other conductive additives which are usually high surface area carbon powders. Like the cathode, a thin coating of the anode mixture will be coated onto one or both sides of the current collector. Electrode performance will vary based on porosity, particle size, distribution and shape, purity, additives, and mixture ratios. Uniformity of electrode manufacturing is key to prevent formation of lithium plating or premature cell failure.

At present, there are three major kinds of carbon which are used as the anode active material in Li-Ion cells:

(a) graphite types (highly structured)
(b) coke types (less structured)
(c) non-graphitizable (hard) carbon type (highly disordered).

In order to achieve a high energy density, the capacity of the primary carbon must be as high as possible. To this end, carbon material with large lithium ion capacities similar to the highly structured graphite's are used to maximize the stoichiometry of LiC_6. The carbon acts as a host material which allows the lithium ion to occupy sites between the graphene planes. The energy density of graphite material is generally better over other carbons (hard, non-graphitized) due to the cell's higher average operating voltage. The most common material presently used in space cells is mesocarbon microbead (MCMB), a spherical graphite particle. Graphite material generally experiences a larger volumetric change during intercalation than hard carbon, which can stress the electrode structure and possibly impact cycle life.

7.1.3 Electrolyte

The electrolyte is a medium in which lithium ions are transported during electrochemical reactions. A common electrolyte solution in Li-Ion cells contains a LiPF6 salt dissolved in a mixture of organic carbonate solvents. Typical organic alkyl and cyclic carbonates in Li-Ion cells include ethylene carbonate (EC), propylene carbonate (PC), di-methyl carbonate (DMC), di-ethyl carbonate (DEC) and ethyl methyl carbonate (EMC). It is important that the electrolyte has stability across the entire operating voltage range with margin. These solvents are used in different ratios to optimize the electrolyte conductivity, viscosity, and freezing point. Additives can be added to the electrolyte to promote electrode stability and long life.

At high voltages the electrolyte solution is not thermodynamically stable with the lithiated carbon anode which results in the formation of a passivation layer generally referred to as a solid electrolyte interface (SEI). This SEI is initially formed during the cell's initial cycles, known as the formation cycle, following cell activation with electrolyte. The SEI is important as it suppresses further reaction between the electrolyte and electrode while remaining conductive to lithium ions.

7.1.4 Cell Construction

Li-Ion cells are typically configured inside a prismatic or cylindrical case. The electrode stack is therefore cut into a prismatic shape or long strips rolled into a jellyroll format that fits snuggly into the case. The Li-Ion cell stack consists of many layers of anode and cathode electrodes each separated by a layer of polymer separator. It is important that the internal design results in uniform current density across and through the electrode structure. This is facilitated by appropriate tabbing and connection to the cell terminals as well as uniform pressure across the entire electrode surface. Good cell design practices as well as uniform manufacturing processes are important. Additional insulator material may be used to provide secondary protection against internal shorts. In space applications the stack is typically contained in a welded metallic case that contains two terminals and generally a fill port. Prior to sealing the fill port the electrolyte solution will be added to the cell and is nearly fully absorbed in the porous stack. A venting mechanism is designed into the cell to accommodate an overpressurization event.

Li-Ion cells are designed with large surface area electrodes so as to provide adequate rate capability. The capacity of a cell is a trade-off in total surface area, coating thickness, current collector thickness and separator thickness. One common degradation mechanism in Li-ion cells is lithium plating on the anode. The primary means of preventing plating is by sizing the negative (anode) approximately 10% larger capacity than the positive (cathode). The actual capacity ratio is a trade-off between the desire for higher capacity cells and longer life, as well as the need for a safety factor to resist abuse conditions. This explains why each Li-Ion cell design may have a different safe voltage range specified by the manufacture despite having similar Li-Ion chemistry.

7.1.5 Performance Degradation

When operating at nominal conditions the typical degradation that is measurable is an increase in impedance and capacity loss. This type of degradation will generally result in a gradual decay of available energy to the satellite load and facilitate prediction of remaining on-orbit battery life. Increased cell impedance will result in higher peak temperatures later in life. Other end-of-life failure modes may be more sudden as from a cell leak or internal short. Electrolyte leakage can occur through terminal seals, fill ports, or as a result of internal corrosion and eventually result in an open circuit while operating in the vacuum of space. Internal cell shorts can occur from foreign object debris (FOD); micro shorts through the separator, lithium plating, and dendrite formation through the separator. As long as the thermal dissipation from these shorts does not lead to thermal runaway, the cell will fail in a benign manner. See additional discussion in paragraph 7.3.

7.1.6 Temperature Considerations

Li-Ion batteries typically operate best near room temperature (e.g., 15 and 30 deg C). As operating temperatures go below the nominal temperature range there is a noticeable change in cell performance. The voltage profile for one particular type of Li-NCA cell over a temperature range of 10 deg C to 30 deg C is shown in Figure 7-1. For this design there was a 10% reduction in capacity, and the resistance increased by a factor of 1.65 at 50% SOC as shown by a reduction in discharge voltage. Each cell design will have a different capacity and voltage response. This higher resistance results from the reduced electrolyte conductivity and reduced Li+ diffusion. For liquid electrolytes the mixture of the electrolyte solution will determine the cell freezing point, which typically ranges between -30 and -50 deg C.

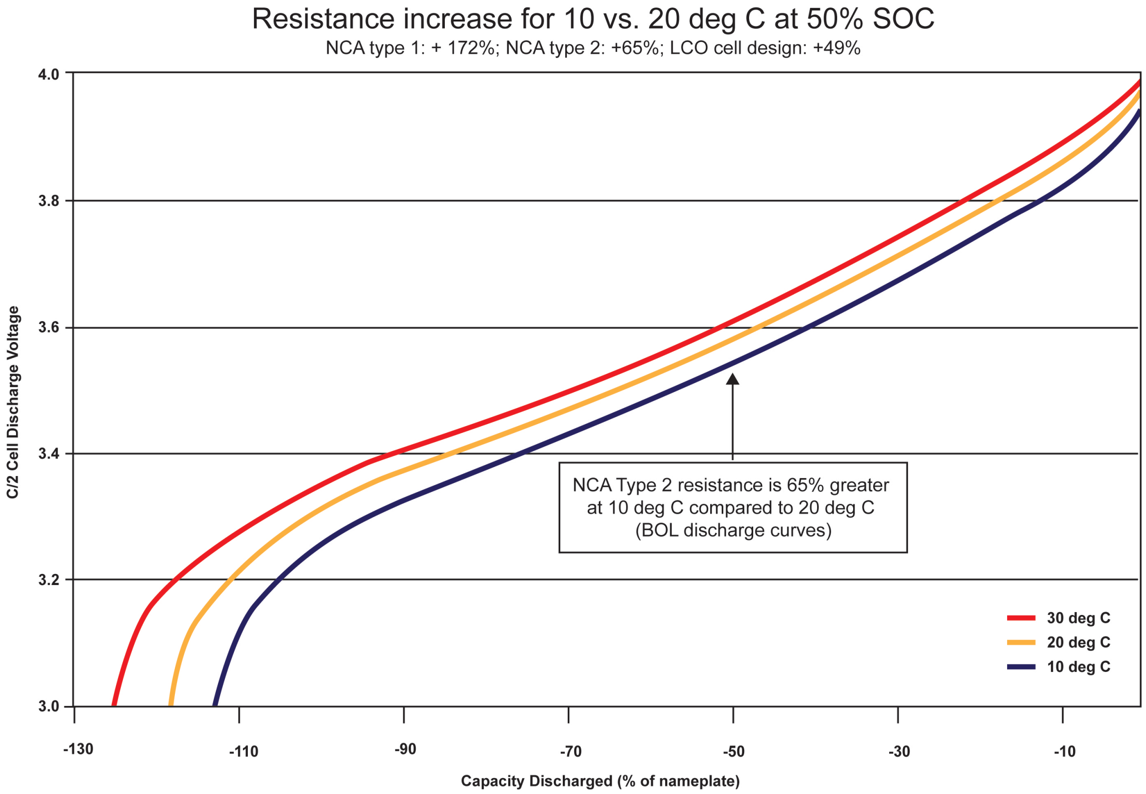


Figure 7-1. Li-NCA cell voltage and resistance as function of temperature.

At these colder temperatures there is a risk that the negative plate potential may reach the lithium plating potential during charge. The potential will vary as a function of the current density, thus limited operation at a reduced current may be possible. Lithium plating will result in increasing the SEI further and also results in further loss of available lithium. As the cell temperature is increased lithiated carbon will react with the electrolyte resulting in thicker SEI and further reduction in available lithium. When the cell is exposed to higher operating temperatures the stability of the SEI layer is affected that can lead to thermal runaway. If this reaction continues without adequate cooling it can eventually cause an abnormal exothermic reaction within the cell that can result in thermal runaway and cell venting. In a non-vacuum environment, fire is likely due to the flammable electrolyte solution.

The impact of temperature on life is still being evaluated in on-going life tests. Temperature effects can vary depending on the active materials and electrolyte solution in a particular cell design and operating conditions. As cells degrade over life, an increase in internal resistance is commonly observed resulting in higher heat dissipation towards end-of-life. When using a cell design that shows a large difference in temperature as a function of either performance or life, one may consider how to optimize battery performance and life by having the capability to adjust operational temperatures during different phases of the missions.

Additional discussion included in Section 7.2.3 Thermal Configuration.

7.1.7 Overcharge

Electrode materials used in Li-Ion cells show a direct capacity relationship as a function of charge voltage for the cell. The higher the cell charge voltage, the higher the capacity. Despite having a capacity continuum, space cell designs are generally balanced for operating up to 4.0 to 4.2 V. This means the cells were designed with sufficient carbon to operate at these maximum voltages. Overcharge can also occur from excess charge current within a nominal voltage range resulting in localized regions of overcharge. If the cell is charged above this voltage, excessive removal of lithium from the cathode can degrade the cathode structure by oxygen evolution which is an exothermic reaction. Likewise, overcharge of the anode can result in lithium plating. Both of these modes can lead to an abnormal increase in impedance or capacity loss.

If these reactions continue without adequate cooling it can eventually cause an abnormal exothermic reaction within the cell that can result in thermal runaway and cell venting. The more severe the degree of overcharge, the more likely a thermal runaway event will occur. In a non-vacuum environment, fire is likely due to the flammable electrolyte solution.

7.1.8 Discharge Limitations

Cell manufacturers will define a minimum operating voltage for their Li-Ion cell design, generally around 3 V. If the cell is discharged below this level it is considered to be in a state of over-discharge. At this point the anode current collector potential is rising and if it exceeds the current collector's dissolution potential, it will result in corrosion and dissolution of metallic ions into the electrolyte. In addition, if the anode potential rises too high the SEI layer can decompose. On subsequent recharge, available lithium is required to reform the SEI layer and the dissolved metallic ions plate as metal onto the negative electrode surfaces. Cells with copper current collectors can lose a substantial amount of capacity in a short period of time, which eventually leads to a shorted cell condition. It has been reported that Li-CoO_2 cells with a titanium current collector can be discharged to zero volts for 14 days at room temperature and not experience capacity loss, but at 37 deg C capacity loss occurred (Ref 2). However, in satellite applications where cells are connected in series it is possible for some cells in the battery to experience voltages below zero volts (negative cell voltages). This may occur when a battery is inadvertently discharged to a lower than normal voltage and series connected cells are in an unbalanced state or degraded non-uniformly. This aspect needs to be considered for both copper and titanium current collectors cell designs.

Due to discharge limitations in most Li-Ion cell designs the need for reconditioning or discharge circuits has been debated. A recent test on a NCA cells has shown that a regular complete discharge to 3.0 V can recover capacity (Ref 3). The capacity increase is likely from a slow Li redistribution in anode by potential gradients. On-orbit capability to perform periodic discharge on flight batteries may be beneficial but not entirely compelling at this time. Additional testing is warranted to evaluate the performance and life benefits of periodic discharge to low voltage.

7.2 Li-Ion Battery

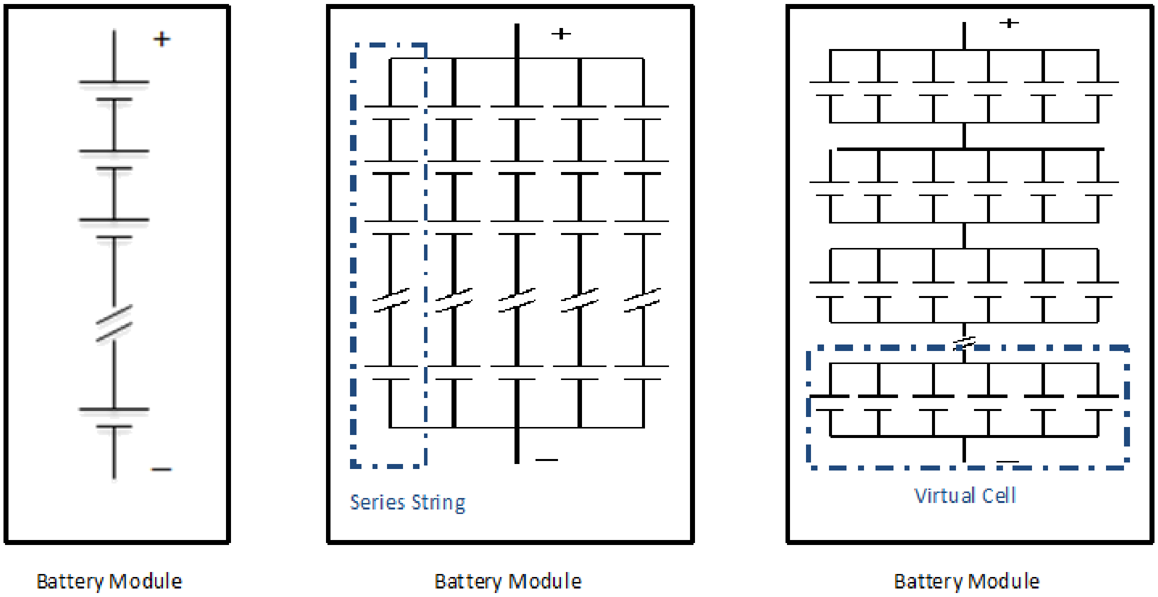
7.2.1 Electrical Configuration

Depending on the battery size and allocated space within the spacecraft, the battery design may consist of either a single battery module or multiple battery modules electrically connected in series, but located at different points on the spacecraft. Within the battery various cell-level electrical configurations have been adopted. Below are three topologies that are presently used in space applications:

a. **Series Connection**. This is the traditional design where a group of cells are electrically connected in series. The capacity of this configuration is equal to the capacity of a single cell. The series string voltage is equal to a single cell voltage multiplied by the number of cells connected in series. Well matched cells with uniform thermal control are required so that cells electrically cycle at a uniform SOC and degrade at a uniform rate. As loads increase or decrease in unregulated power subsystem architectures, cell capacity may need to increase or decrease to optimize satellite weight. In a regulated power subsystem, cells may first be added or removed in the series string to adjust for spacecraft load within the operating voltage range. The series string approach generally requires a large format cell to support a single or multiple battery architecture. This configuration generally builds in redundancy features to accommodate credible failures such as cell shorts and cell opens. A cell short will reduce the series string voltage by one cell. A cell open (or cell with high resistance) will stop or significantly reduce current flow in the series string unless current is bypassed around the opened cell. Due to the significant implication of a single-cell failure either from a short or cell open, cell balance and cell bypass hardware is required for highly reliable programs.

b. **Series – Parallel Connection**. This configuration creates a battery by taking multiple series strings and connecting the output of each series string to a common point. The battery capacity will equal the cell capacity multiplied by the number of series strings. The battery voltage will equal the cell voltage multiplied by the number of cells in a series string. The advantage of this configuration is that it requires only a single charger to charge all series strings. It is generally used in conjunction with small cell sizes where the loss of a single string is a small percentage of the entire battery. As a result, use of cell balance and cell bypass hardware is eliminated and cell safety features, such as current interrupt device (CID) and positive temperature coefficient (PTC) polyswitch, are implemented to provide overcurrent and overvoltage protection at a cell level (see section 16.4.2). This design rarely includes cell level voltage measurements or series string current monitors, so it is unknown how well balanced the strings are once on-orbit. In the event of a cell short the remaining cells in that string may experience over-discharge or overcharge conditions at which point the string would be lost. In the event of a cell open the entire series string will be lost since bypass circuitry is generally not used. This design requires tighter cell matching of beginning-of-life self-discharge rates so that all cells operate at a similar SOC due to lack of cell balance hardware.

c. **Parallel – Series Connection.** This configuration takes a group of cells connected in parallel (typically 3-6 cells equal virtual cell) and then electrically connects their output in series with other similar virtual cells. The capacity of this design is equal to the capacity of a single cell multiplied by the number of cells in parallel. The voltage is equal to a single cell voltage multiplied by the number of virtual cells in the series string. This configuration minimizes cell balance and cell bypass hardware and also allows the battery capacity or voltage to be adjusted in increments while using the same cell design regardless of power subsystem architecture. It is important that cell capacity and resistance is well matched at beginning-of-life and that good thermal control is maintained over life to facilitate uniform degradation rates among all cells. As an example, a mis-match in parallel cell resistance internal to the cell or from thermal gradients would result in the preferential discharge of good cells with lower resistance. Cells with higher use could experience higher degradation rates. Another consideration is that a cell short would dissipate the energy from all cells in the parallel string even if bypassed from the battery's series connection. A virtual cell with a single cell open could still function but at a higher DOD. Due to the significant implication of a single-cell failure either from a short or cell open, cell balance and cell bypass hardware is required for highly reliable programs.



Series String　　Series-Parallel String　　Parallel-Series String

Figure 7-2. Battery cell configuration.

Other electrical considerations include minimizing voltage drop within the battery by configuring the cells to minimize inter-cell and connector harness length and maximizing the harness cross-section to limit heating and battery level resistance. Redundant battery and cell level voltage sense lines are required for charge control, cell balance, and telemetry, each containing a series fuse to prevent an inadvertent cell short. Additional voltage telemetry via spacecraft umbilical cord facilitates availability of voltage readings once on pad without needing to power up the spacecraft. In most large cell format designs bypass switches are included for each cell or virtual cell which are either autonomous or require external control. To minimize the likelihood of a short to ground any electrical path within the battery requires double insulation. Letdown circuits within the battery can be used as a method to discharge the battery from high to low SOC without the use of external test equipment or provide on-orbit reconditioning to an acceptable low voltage. Other electronic hardware may be mounted to the battery such as disconnect relays, cell balance hardware, depleted battery prevention electronics, and/or current sensors. All piece parts mounted on the battery require their separate qualification and acceptance tests to validate their design and workmanship prior to installation in the battery.

7.2.2 Mechanical Design

The battery design needs to provide structural integrity for all potential mechanical loads and environments. The battery unit is exposed to severe shock and vibration environments during various stages of the mission. At lift-off rocket engine firing exerts intense acoustic pressure on the entire spacecraft. These acoustic pressures induce vibration to the internal spacecraft structure. In addition, the spacecraft experiences intense transient impulses or shocks during engine ignition/shutdown, solid rocket motor jettison, staging, fairing, and spacecraft separation. The acoustic-induced vibration and shocks have the potential to damage the battery unit. To ensure survivability the battery unit requires preflight shock and vibration testing (acoustic testing is limited to units having large surfaces) as defined in SMC-S-017.

In order to verify that the battery design has a high probability of success mechanical analysis is performed prior to building a unit. To assist in the evolution from conceptual design to flight article it is common for mechanical development tests to be performed on an engineering cell virtual cell, or battery module or unit. Resonance searches of a unit should be conducted to correlate with a mathematical model and to support design margin or failure evaluations. Development tests and evaluation of vibration and shock test fixtures should be conducted prior to first use to prevent inadvertent over-testing or under-testing, including avoidance of excessive cross-axis response. As part of these mechanical tests consideration must be given to the battery operational SOC during launch as this may impact internal electrode compression. Qualification and acceptance level unit tests are performed per SMC-S-017 so that any design flaw or workmanship issue is detected prior to installation and test at the spacecraft level.

7.2.3 Thermal Configuration

Li-Ion battery performance is significantly affected by operating temperature. The battery design needs to accommodate battery heat dissipation from the cells, harness and other piece parts as well as maintain minimum temperature during periods of low heat dissipation. In order to dissipate heat the cells are typically mounted within a thermally conductive module or between plates in order to conduct heat to a base plate that ultimately rejects the heat to space via a thermally passive or active design. Both primary and redundant heaters are mounted on the cells or thermal modules/plates to maintain minimum temperature requirements. The heaters are sized to provide sufficient heat to maintain the cell minimum operating temperature when the heaters are operating at their maximum voltage and <80% duty cycle. Thermistors are typically mounted on the cells for temperature telemetry and heater control by the on-board computer or other heater circuit. A sufficient number of flight thermistors are required to (1) monitor the hottest and coldest cells of the battery and (2) to accommodate number of heater circuits, cell failures, and software averaging methods that may eliminate a high or low reading.

Thermal requirements need to be established to ensure mission life will be met. These include minimum and maximum cell temperatures, operational average, maximum cell-to-cell temperature gradients within a virtual cell, and battery and cell temperature gradients. Minimum, maximum, and average operating temperatures should be selected that maximize performance for mission and cell design as discussed in 7.1.6. Maximum cell-to-cell temperature gradient at the battery level is limited to 3 deg C for virtual cells as higher cell-to-cell temperature gradients can result in unequal current distribution in a parallel connection. For series connected cells, cell-to-cell temperature gradients are limited to 5 deg C to limit non-uniform degradation over life. Cell gradients from top to bottom can vary with cell size but are typically maintained at <5 deg C so as to maintain uniform current density across all electrode surfaces. It is important to consider end-of-life temperatures as cell temperatures typically increase over life. To facilitate meeting these requirements, flight batteries are generally thermally isolated from the spacecraft. An important aspect of the battery design process is to validate that the on-orbit battery cell temperatures will remain within the temperature range that has been demonstrated by ground qualification life test.

A key aspect of the battery design process is the thermal analysis. The analysis validates that the design will meet temperature requirements over the mission life as measured at the cell. Individual piece parts (e.g., bypass switches, relays, etc.) mounted on the battery have separate thermal requirements that also need to be validated as part of this process. Below are items to consider when performing a battery thermal analysis:

a. Cell heat dissipation needs to be characterized for the specific Li-Ion cell design as, unlike Ni-H_2, the thermoneutral voltage varies as a function of cell SOC and cell chemistry as shown in Figure 7-3. The thermoneutral voltage is the operating voltage where no cooling or heating occurs in an electrochemical cell and is typically used to estimate cell dissipation during cell operation given the operating voltage and current as shown below:

$$Q_{cell} = I * (V_{th}-V_i)$$

Q_{cell} = Heat dissipated from cell in watts. If q is negative the overall process is endothermic and the cell cools. If Q_{cell} is positive the overall process is exothermic and the cell heats. Heat does not include I^2R dissipation external to cell terminals such as from inter-cell connectors and terminal harnesses, but does include all I^2R dissipation from cell terminals and internal conductors.

I = Cell charge or discharge current in amperes. I is positive for charge currents and negative for discharge currents.

V_{th} = Thermoneutral voltage in volts as a function of SOC for a specific Li-Ion cathode and anode design.

V_i = Cell terminal voltage in volts while under load.

It can be noted that during charge if V_i is greater than V_{th} the process is exothermic and the cell heats. For discharge if V_i is greater than V_{th} the process is endothermic and the cell cools.

Since heat dissipation is generally measured from a beginning-of-life cell, an additional end-of-life cell dissipation factor needs to be included. End-of-life dissipation can be obtained by adding additional delta dissipation from resistance growth or watt-hr efficiency based on life test measurements or projections.

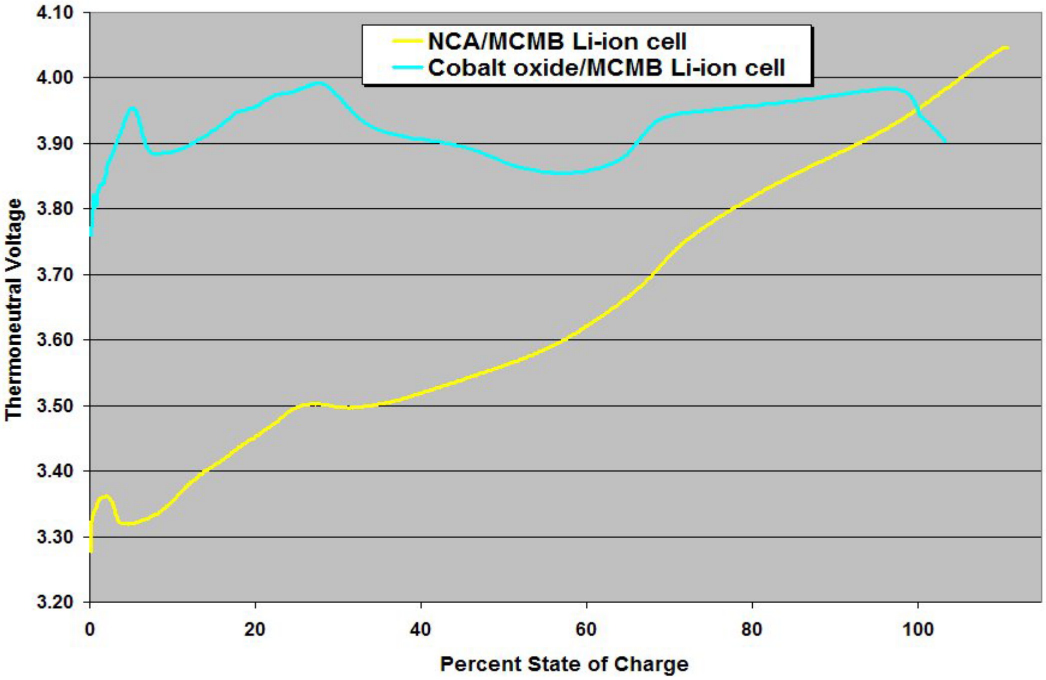


Figure 7-3. Thermoneutral voltage measured for Li-NCA/MCMB and Li-CoO_2/MCMB cells.

b. The battery thermal analysis needs to demonstrate/include:
   i. On-orbit worst case hot and cold heat dissipation from the cells and other battery hardware (e.g., cell interconnects, harness, relays, bypass switches) external to the cell terminals can be accommodated with required cell failure case while operating within temperature limits as defined in the battery specification.

      Note: Multiple thermal analysis cycles should be run to validate temperature stability.
   ii. Post-launch battery temperature through payload activation to be within operational limits.
   iii. On-orbit temperature requirements are met under worst case cell, heater and heat pipe failed conditions with adequate radiator margin to accommodate any post thermal vacuum test corrections.
   iv. Any heating from sun impingement as it relates to peak temperatures and cell-to-cell gradients.
   v. Model correlation with thermal characterization test performed in vacuum on the flight cell, virtual cell, module, or battery. Thermal conductance tests can also be performed to verify heat transfer paths from the cell to the radiator or across battery to spacecraft interfaces.
   vi. Qualification and flight battery will successfully demonstrate temperature and heater operation in thermal cycle and thermal vacuum test as defined in SMC-S-017. Following unit level thermal vacuum test, the thermal model needs to be correlated with the thermal vacuum data. Any updates to the model will require updates to the mission analysis to re-verify requirement will be met.

7.3 Li-Ion Lessons Learned

Li-Ion has exhibited problem areas similar to those for Ni-H_2 and Ni-Cd technologies in the past. These include, but are not limited to, cell and battery short circuits, thermal runaway, test and handling anomalies, and in-service failures. More severe consequences exist for Li-Ion technology due to the potential for significantly greater energy release and breach of containment, fire and explosion, and collateral damage. Prevention and containment are much more important for Li-Ion. Multiple and redundant levels of protection are required. Li-Ion cell failures, like those of other technologies, are expected to occur despite failure preventive features; the battery system needs to accommodate Li-Ion cell failures.

7.3.1 Manufacturing Defects Observed

Even the best manufacturers have occasional cell or battery defects that can result in either catastrophic or non-catastrophic failures. Some typical defects seen include:

a. Cell leaks from weld porosity, weld alignment, contaminated weld surfaces either at BOL or latent.

b. Marginal case to terminal electrical isolation resulting in high resistance that gives Li plating and gas generation over many years.

c. Poor anode/cathode plate alignment. Even one misaligned plate pair can start Li-plating buildup.

d. Non-uniform or excessive stack compression can produce dry regions and initiate Li-metal shorting structures within the stack.
e. Mis-wiring cells and other components in battery.

To mitigate these defects 100% screening, quality control and inspection at both cell and battery levels are critical for Li-Ion technology.

a. CT scan to verify cell design as part of qualification
b. 100% cell inspection with high resolution x-ray to verify workmanship of weld geometry, stack alignment, and tabs to terminals
c. 100% visual inspection of stacks prior to insertion into case
d. 100% visual inspection of stack and tabs prior to closing case
e. 100% leak check of cells prior to sealing
f. RGA leak check of cells after environmental acceptance tests
g. Charge retention screening of sufficient duration
h. Stringent requirements for terminal to case isolation
i. Verify and cross-check all internal battery connections and functions

7.3.2 Cell/Battery Handling and Test Lessons

Storage, handling, and test procedures need appropriate safeguards to minimize risk to flight hardware. Types of handling issues seen include:

a. Mating with unauthorized, unverified, or unmarked test cables or hardware
b. Inadequate procedures for control over testing, handling, or storage
c. Lack of independent hardware protections in testing or storage, such as:
    i. Chamber or battery over temperature and under temperature
    ii. Cell over-voltage and under-voltage interlocks
    iii. Computer watchdog – do not depend solely on software
    iv. Detection of stale data during testing

The responsible engineer should anticipate the worst case scenario, not depend on any single protective device or in-cell protections alone (fusible links or other CIDs, PTC devices, shutdown separators, etc.).

7.3.3 In Service Failures and Lessons

Failure modes observed for Li-Ion (to date):

a. Cell internal short circuits and venting (>2 deg C/sec temperature rise)
b. Internal cell fires and venting (>2 deg C/sec temperature rise)
c. Cell venting from internal pressure rise (CO2 oxidation product)
d. Soft shorts causing cell imbalance that charger cannot handle

e. Cell balancing current inadequate in LEO (allowed some elevated voltages)
f. Capacity loss (low voltage at max DOD)
    i. Typically accelerates significantly after 20–40% loss
    ii. Accelerates at higher peak charge voltages
g. Cell resistance increase (>100% at EOL, imbalanced cell resistances)
h. Cell leak at weld or seal causing high impedance
i. Broken internal tabs or connections during vibration or cycling

Effective mitigation steps are to stop charging upon detection of any verified anomalous cell temperature or voltage excursion as charging provides positive feedback for runaway. Secondly, use lowest peak charge voltage consistent with capacity margin needs.

Cycling failure mechanisms verified in Li-Ion cells include:

a. Plating of metallic lithium that eventually results in cell short or fire
b. Imbalance between anode and cathode SOC
c. Electrolyte oxidation that occurs normally or anomalously from parasitic processes
d. Resistive SEI layer growth in anode material
e. Loss of binder conductivity in anode or cathode
f. Weld flaw propagation and seal relaxation to cause cell leaks

Diagnostics found to be effective include life test for worst case operational condition that includes significant stress margin to detect unexpected degradation processes. CT scans of well-cycled cells can detect lithium plating. DPA of well-cycled cell to verify expected (safe) degradation processes and RGA for detection of leaking electrolyte.

7.3.4 Technology Maintenance Lessons

With any cell chemistry there is a high probability of key material obsolescence especially given the long test periods for life verification coupled with longer procurement times. The active material availability is driven by commercial markets. Storing stockpiled material can be an effective method to accommodate procurement schedules. Validation of material storage methods can be challenging.

Cell or battery manufacturer may move to a new facility or the manufacturer may “improve” designs or processes. Changes are sometimes unintentional or the customer may not be notified of change until after the hardware is built. The time and cost to re-qualification can become prohibitive.

Accelerated life tests for sample cells from each lot provide a means to detect unintended changes. It also provides a mechanism to quantify lot-to-lot variability for reliability estimation. One normally expects to see consistent cell behavior over long procurement periods. Individual life tests for each “improved” design would provide a way to assess the impact of the improvements on life.

8. Li-Ion Charge Management Methods

Li-Ion batteries require careful attention to end-of-charge voltage (EOCV) and currents. Unlike Ni-H2 and Ni-Cd battery systems, Li-Ion batteries do not exhibit a significant temperature or pressure rise as they approach their normal EOCV. However, Li-Ion cell voltages can provide an accurate measure of the relative SOC of the battery. The relative simplicity of Li-Ion charge management methods become apparent from a brief review of Ni-H2 and Ni-Cd battery charge management methods.

8.1 Battery Charge Management Methods for Other Space Battery Technologies

Sealed Ni-H2 cells generate hydrogen as they charge, and consume hydrogen as they discharge; this results in a cell pressure that is proportional to the cell SOC. By monitoring the cell pressure through a strain gauge and the accompanying electronics, one can determine the pressure of a cell and, by extension, the relative SOC of the cell. Although pressure is generally linear with respect to cell SOC, one must also consider temperature effects on pressure. Also, residual pressure builds up in the cell over life and must be accounted for in determining an appropriate end of charge pressure. However, based on a particular operating regime and a repeatable thermal environment, it is possible to control Ni-H2 battery charging based on a pre-determined cell pressure. This pressure will generally increase over life. Seasonal calibration procedures may be required to determine the optimal charge cutoff pressure for the eclipse season.

Ni-H2 batteries also exhibit a characteristic coulombic recharge ratio. By monitoring the battery current through discharge, one can recharge the battery based on a known recharge ratio. Recharge ratios in the range of 1.05 to 1.15 are typical for Ni-H2 batteries used in a geostationary orbit. Ni-H2 cells charge more efficiently at higher charge rates.

Ni-H2 cells exhibit a high self-discharge rate, especially at high SOC. Therefore, after fully charging the Ni-H2 battery it may be necessary to maintain a “trickle” charge equivalent to the expected self-discharge rate.

Ni-H2 batteries exhibit a sharp temperature rise as they approach 100% SOC. Because of this, temperature must be carefully monitored and be factored into the charge management method.

Until recently sealed Ni-Cd batteries have been used in space applications. Like Li-Ion systems, Ni-Cd battery charging is performed primarily by charging to a desired EOCV. The Ni-Cd cells are typically charged at constant current until they reach approximately 1.45 V at 30 C. The voltage at which the cell is fully charged is temperature dependant; therefore, the end of charge threshold voltage may be adjusted according to the cell operating temperature. Also, the optimal EOCV increases with life, therefore a number of Voltage versus Temperature curves (VT curves) may be employed over the operational life of the satellite.

Like Ni-H2, Ni-Cd cells exhibit a rapid increase in temperature if the cell exceeds 100% SOC. Therefore, it is critical that Ni-Cd charging systems utilize a temperature sensing device that terminates cell charging upon detection of a temperature rise.

8.2 Li-Ion Battery Charging and Battery Charge Management

Li-Ion battery charge control is most often based on monitoring and controlling battery and/or cell voltage. The desired EOCV is pre-determined based on cell chemistry and life expectations. Li-Ion battery charging systems rely on a battery and/or cell voltage measurement system and charge current control electronics and algorithms that use voltage measurements as a control loop feedback element.

A number of voltage measurands might be used to control the battery current at EOC. Voltage monitoring may be based on the total battery voltage, the average cell voltage, the maximum cell voltage, the minimum cell voltage, or a combination of these measurements. In practice differences in voltage will develop between series connected cells or virtual cells; the magnitude of the difference will depend on cell chemistry, parasitic leakage paths, the environment, and the effectiveness of the cell balancing mechanisms to control divergence. If very small differences in cell voltages are predicted, then the average cell voltage, or total battery voltage, may be the key voltage control variable. If high cell divergence is expected, it may be desirable to manage battery charge based on the maximum cell voltage.

Given the same EOCV, more energy can be stored in a battery when using the average cell voltage as a control variable compared to using the maximum cell voltage. When using the average cell voltage method, some cell voltages will be slightly higher and some cell voltages slightly lower, than the average. Where large cell to cell voltage divergences are expected this method has a disadvantage in that the cells with the highest voltages may exceed the optimal voltage for life considerations. Basing the EOCV on the highest cell voltage gives more control over the highest voltage cell; but this method limits the total battery energy by undercharging the cells with lower voltages.

No matter what specific voltage measurements are used to control battery SOC, the end of charge voltage threshold is preferably a programmable value that can set by ground commanding. This provides the greatest flexibility in controlling the optimal EOCV.

The electronics employed to charge the battery depend somewhat on the EPS topology. In battery dominated bus topologies, battery charge current can be controlled by regulating solar array current; battery charge current is reduced by reducing solar array current to the battery/bus. In fully regulated buses, a separate battery charger is often employed. In either case, battery current can be controlled through at least two basic methods that result in the desired EOCV.

Method 1: Constant Current, Constant Voltage Charging

In this method, the battery is first charged at constant current. This current may be limited to a maximum value, or it may use all available solar array power to charge the battery. Once the battery or cell voltage reaches the programmed EOCV the control circuit reduces the battery current in order to maintain a constant voltage. This results in a battery current profile that drops in somewhat of an exponential fashion. After some time the current required to maintain a constant voltage reduces to near zero. While operating in constant voltage mode, the cell is said to be in "taper charge." Figure 8-1 shows a typical profile of cell current and voltage using Method 1.

Method 2: Programmable Constant Current Step Charges

In this method, the battery is first charged at a programmed high rate. The battery is charged until the battery or cell voltage reaches a pre-determined value, upon which the controller charges the battery at a reduced programmed rate. This process is repeated until the desired EOCV is reached at the lowest desired charge rate. Figure 8-2 shows a typical profile of battery current and voltage using Method 2.

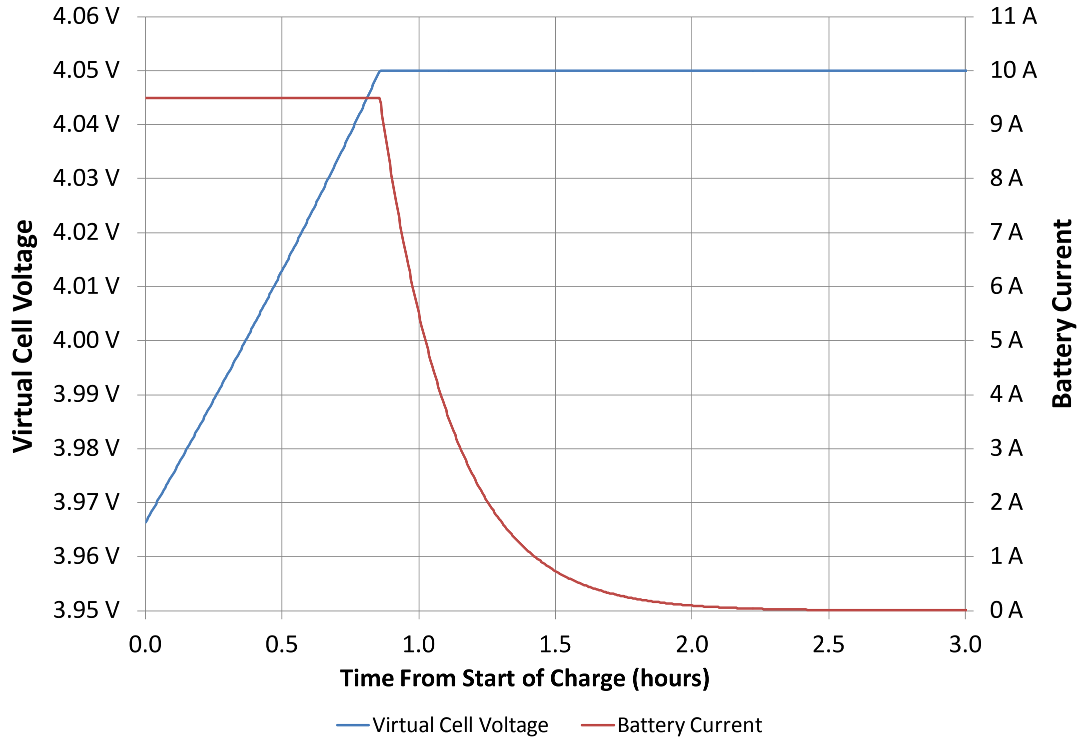


Figure 8-1. Example of taper charge voltage and current profile for Method 1.

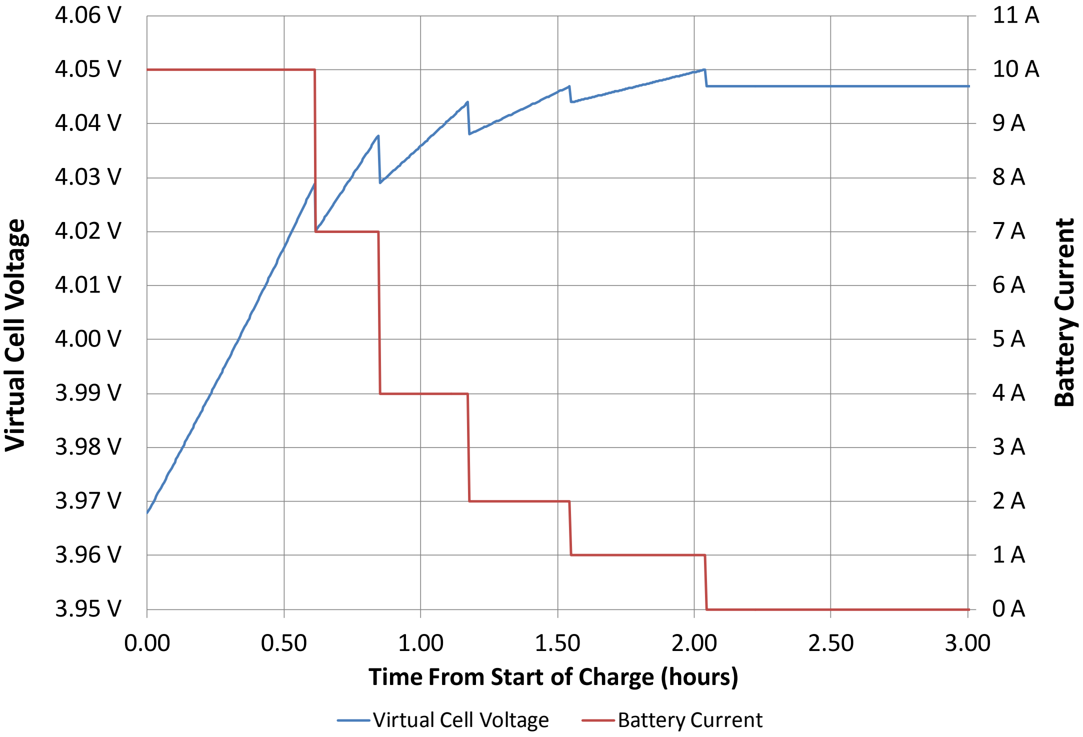
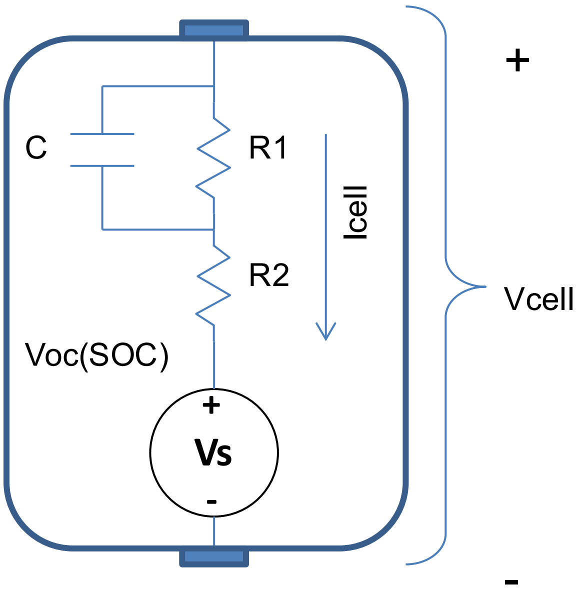


Figure 8-2. Example of programmed step charge current and voltage profile for Method 2.

8.3 Li-Ion Cell Resistance

Both charge methods are affected by internal cell resistance. Li-Ion cells have a measureable cell resistance or polarization voltage. That is, the cell voltage is not only determined by SOC, but by the magnitude and direction of cell current as well. If we model a cell as a perfect voltage source in series resistance, then the terminal voltage of the cell is Vcell = Voc(SOC) + Icell * Rcell, where Voc is the open circuit voltage of the cell as a function of state-of-charge (SOC), Rcell is the internal resistance of the cell and Icell is the current through the cell. This means that the terminal voltage of the cell will change instantaneously with changes in current, even though there is no instantaneous change in SOC. Because of apparent capacitive effects within the cell, some of the voltage change occurs instantaneously while some of the voltage change occurs over a period of minutes. A common Li-Ion cell model is shown in Figure 8-3.



Rcell = R1 + R2

Vcell = Voc(SOC) + Icell * Rcell

Figure 8-3. Simple Li-Ion cell model.

In this simple model, "Rcell" represents the combination of resistive type elements including terminal resistance, electrolyte resistance, diffusion, and concentration gradient effects. "Vs" represents an open circuit cell voltage as a function of cell state of charge.

The internal cell resistance is what gives the Method 1 charge current its characteristic shape. Li-Ion cell resistance increases as the cell ages, it also *increases* with *decreasing* temperature. As the cell impedance increases, the cell will begin taper charge earlier and the current will fall off more slowly. This is illustrated in Figure 8-4.

This phenomenon limits the highest achievable SOC, especially in LEO orbits where very little time is available for battery recharging. Figure 8-5 shows the energy returned to the cell as a function of time. These plots correspond with the plots in Figure 8-4; in both cases the initial cell voltages are identical. The increased cell resistance causes the battery to enter taper charge earlier and at a reduced current and the battery takes longer to recharge relative to the cell with lower resistance.

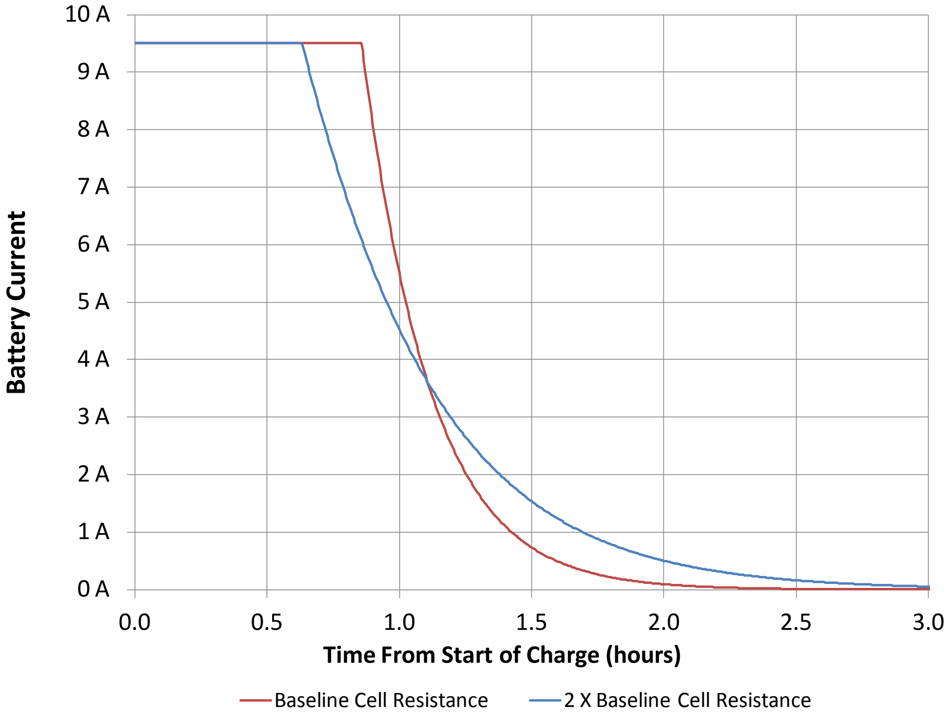


Figure 8-4. Impact of resistance change in taper current profile for Method 1.

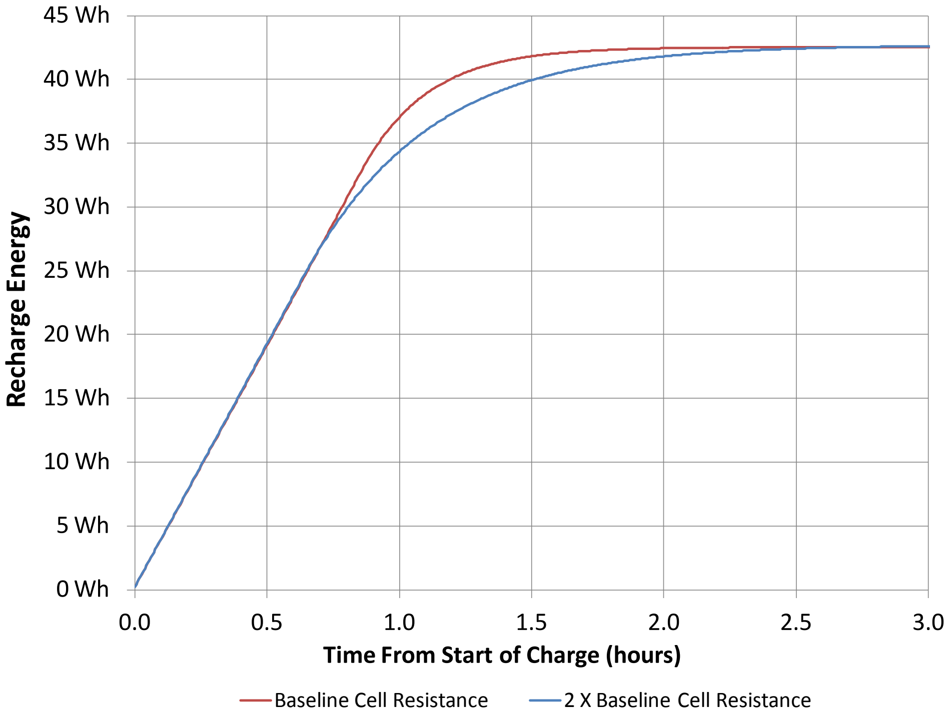


Figure 8-5. Impact of resistance change in energy recharge profile for Method 1.

Referring again to Figure 8-5, if the recharge interval is limited to 1 hour, such as might be the case in a low earth orbit, the cell with increased resistance will accept less recharge energy than the lower impedance cells. In a LEO orbit, the net effect of increased cell resistance is a decrease in the maximum SOC from orbit to orbit.

8.4 Battery Overcharge through Parasitic Current

For both GEO orbits and some LEO orbits the solar insolation period becomes long enough for the battery to reach the desired end of charge voltage and the battery current will reduce to zero. Because the self-discharge rate of Li-Ion batteries is extremely low, "trickle" charging is not required. Li-Ion cells are extremely efficient at storing charge, even very low charge rates. Any residual current into the cell will cause a voltage increase and may result in overcharge. A 50 Ah cell continuously charged at 10 mA (C/5000) will increase its SOC by nearly 60% over the course of the 137 days between eclipse seasons, even after allowing for self-discharge current.

8.5 Battery Charge Current Ripple versus Life Test Conditions

Ideally, the battery or cell life test should employ a method and charger identical to the method and charger used during mission operations. In practice, the life test is most often performed with specialized test equipment with precise charge current controls. In contrast, the spacecraft battery charger may contain high amplitude AC ripple at the converter's switching frequency. It is desirable that battery current during charging is always positive; this is the most likely condition during cell life testing. Figure 8-6 shows a battery charger with a 1 A peak-to-peak AC ripple current. In this case, the lowest applied average current applied to the battery should be greater than 0.5 A in order to prevent the battery current from cycling between charge and discharge. In order to maintain consistency with the charge method used for life testing, the battery should not constantly cycle between charge and discharge.

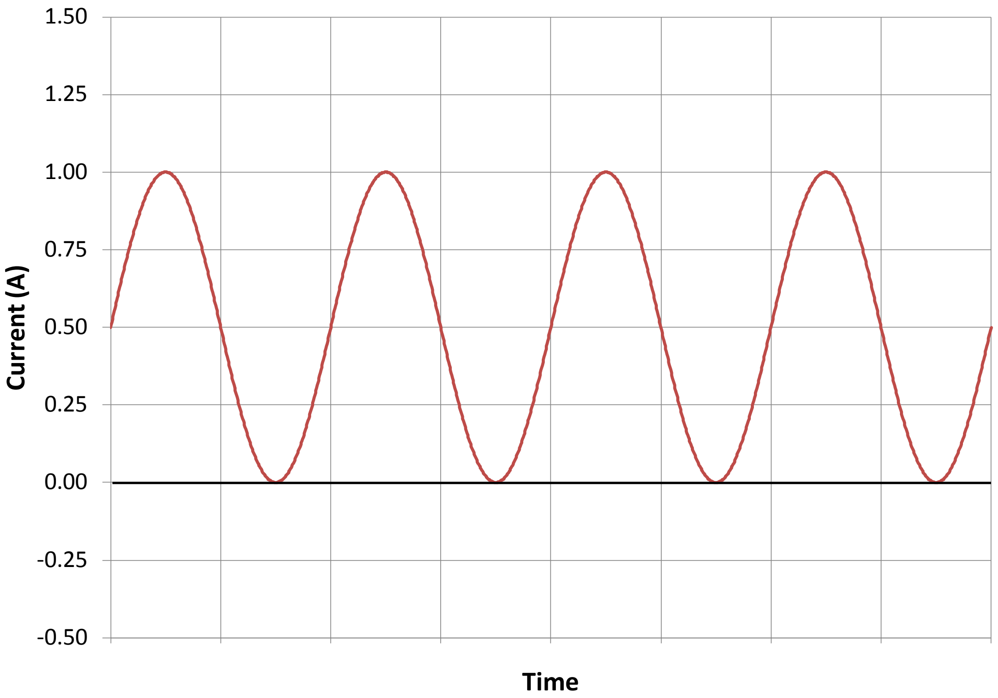


Figure 8-6. Selection of lowest average charge current based on peak-to-peak AC ripple current.

9. Overcharge Protection

Unlike the Ni-H2 cells commonly employed on spacecraft throughout the previous 25 years, Li-Ion cells are generally intolerant to overcharge. With nominal overcharge, Ni-H2 cells experience little if any performance degradation. (Note – this assumes adequate thermal controls are in place to remove the heat generated by the charge inefficiency at high states of charge). Li-Ion cells, on the other hand, undergo electro-chemical changes when overcharged that can result in cell performance degradation, and even outright cell failure with significant safety concerns.

9.1 Overcharge Electrochemistry and Consequences

There is a general relationship that exists with Li-Ion cells – the higher the intrinsic voltage, the greater the SOC (i.e., the greater the available capacity). However there is a point of diminishing return with regard to this relationship; a Li-Ion cell cannot be charged to higher and higher voltages indefinitely without consequence. The point of diminishing return is a function of the cell design, most notably the specific make-up of the cathode, anode, and electrolyte.

If a cell is charged above its intrinsic full-charge state (i.e., if it is overcharged), the anode can become overly lithiated to the extent where lithium intercalation ceases and lithium metal plates out on the anode. Lithium plating of the anode can lead to an abnormal increase in impedance and/or capacity loss. The cathode is also affected by overcharging. Whereas the anode may become overly lithiated, the cathode can become overly de-lithiated, resulting in thermal decomposition, excessive heating, and potentially catastrophic loss of the cell. The catastrophic loss of a cell can result in even more severe consequences – collateral damage to other cells/strings in the battery, collateral damage to other system elements, and/or human injury or death. The potential for human injury or death mandates that overcharge protection be exceptionally robust during the ground test and integration phases of a Li-Ion battery life cycle.

It should be noted that the specified overcharge threshold for a particular cell design is not a “cliff”, in the sense that exceeding the threshold does not necessarily result in severe, immediate, and/or permanent consequences as described above. The severity and/or likelihood of consequences are a function of many factors – the extent to which the threshold is exceeded, the length of time that the threshold is exceeded, the cell’s temperature, and the rate at which the cell is being charged. It is important to consult with the cell and/or battery supplier to determine if there is relevant test data characterizing operation beyond the specified overcharge threshold, and the constraints that the supplier would prescribe to such operation (magnitude of the overcharge condition, duration, and frequency of overcharge events, etc.).

9.2 Overcharge Protection Considerations

Overcharging must be protected against to ensure the long-term viability of Li-Ion cells. The process for preventing overcharge is straight-forward – monitor the battery, battery cells, and/or battery charging system to determine if the prescribed overcharge threshold has been exceeded, and if it has – take appropriate action to reduce and/or limit the SOC to prevent continuation of the overcharge condition.

9.2.1 Monitoring for Overcharge

There are two direct approaches that can be used to monitor for overcharge: 1) monitor the terminal voltage of the battery, or 2) monitor the terminal voltage of the individual cells. Typically, the most assured approach for overcharge monitoring is to measure the terminal voltage of the individual cells.

Regardless of whether cell voltages or the battery voltage is monitored, the possibility of measurement errors must be accounted for when establishing an overcharge threshold against which voltage measurements are compared.

9.2.1.1 Cell Voltage Monitoring

Measuring the voltage of each individual cell in a battery is typically the preferred and most assured method of detecting an overcharge condition. Monitoring individual cell voltages is advantageous because the potential for uncertain knowledge of the battery's cell balance state (see battery voltage monitoring section below) is not a concern. Also, by monitoring individual cells, the specific cell or cells that are experiencing an overcharge condition are readily identified. In battery systems having active CBE, it is typical for individual cell voltage measurements to be made available to the system for fault monitoring and response, readily allowing for detection of an overcharge condition and other cell-level anomalies.

9.2.1.2 Battery Voltage Monitoring

Monitoring the battery voltage, rather than individual cell voltages, can sometimes be a viable method for detecting an overcharge condition:

- If the cells in the battery are known to be balanced, then the battery voltage can be used as a direct indicator of a cell overcharge condition. (It should be noted that although a cell overcharge condition can be detected within the battery, the specific cell or cells in the battery that are overcharged are not known).
- In some instances, the cells can be presumed to be balanced. One example of this is when the battery consists of many small-capacity cells (typically from commercial sources) where large production lots of cells are screened and matched before cells are integrated into the battery. It is worth noting that, due to the large number of cells typically used in such batteries, individual cell voltage monitoring is essentially impractical in any case. For situations where balanced cells can be safely presumed, battery voltage may be used to monitor for cell overcharge.

  Note: caution should be applied whenever there is a presumption of balanced cells. Whether or not cells can be safely presumed to be sufficiently balanced is a function of several factors, including but not limited to: 1) the performance and aging characteristics of the cell design, 2) the manner in which the cells are discharged and recharged, 3) the battery's thermal environment, and 4) the battery mission life.
- In those instances where the battery cells are not known to be balanced, and balance cannot be presumed – battery voltage cannot be safely or reliably used to detect a cell overcharge condition.

9.2.2 Response to Overcharge

The key objective of any overcharge response should be to remove charging current from the battery or the affected cell(s). In fact, discharging the battery or affected cell(s) may be the best action to take, since this should lead to correction of the overcharge condition. In general, eliminating charge current will "safe" the battery in the immediate; discharging the battery does the same but also maximizes the possibility of preserving the battery's health.

Specific actions taken in response to an overcharge condition are a function of several things, including but not limited to:

- The battery's life-cycle phase (e.g., ground test phase, spacecraft integration phase, mission ops phase, etc.)
- The system architecture in which the battery is embedded
- The extent to which the battery is overcharged (higher states of overcharge may warrant more draconian responses than would lesser states of overcharge)
- The type of CBE present in the battery system (if applicable)
- The presence or lack of intrinsic overcharge protection features
- The type of overcharge monitoring employed (cell voltage monitoring or battery voltage monitoring)

For example, as mentioned above, a possible consequence of overcharging is human injury or death. Given that possible consequence, detection of an overcharge condition might warrant autonomously isolating the battery during the ground test phase. However, during mission ops, that could be infeasible – as with single-string systems, for example. Switching to redundant charge control hardware might be the proper response during that life-cycle phase.

9.2.3 Back-up Overcharge Protection

A back-up means of detecting and responding to an overcharge condition is typically warranted for most systems. Even in a system that is nominally single-string, back-up monitoring should be considered in light of the possibility for human injury or death that can result from overcharging a Li-Ion cell.

One approach is to employ individual cell voltage monitoring as the primary overcharge detection method, and to use battery voltage monitoring as a back-up method. Another approach, especially for systems without individual cell voltage monitoring, is to use redundant battery voltage monitors. Depending on the overall architecture of the power subsystem, it may be possible to use bus voltage monitors as a back-up to the battery voltage monitor.

Due to the likelihood that a failure in the nominal charge-control system is the root cause of an overcharge condition, care should be taken to assure that the back-up overcharge monitor and response elements (hardware, firmware, software, etc.) are independent and isolated from the elements used in the nominal charge-control process.

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10. Cell Balance Electronics

A unique feature of most Li-Ion battery power systems is the need for battery cell balancing. Li-Ion battery cells can be damaged from overcharge or over-discharge, so it is extremely important to maintain the cell voltage (or SOC) within its design limits. The typical operating voltage range of a Li-Ion battery cell varies between 3.0V and 4.0V. Cell balancing helps to maximize battery capacity utilization. Failure to maintain cell balance over long periods can cause cell divergence leading to overcharge or over-discharge thus degrading battery reliability.

10.1 Definition

Cell balancing is a process of controlling the voltages of all the cells within a battery to be the same. Cells within virtual cells are balanced since the cell voltages of parallel-connected cells have to be the same. Cell balancing serves to equalize the voltage of battery cells series connected cells in a battery.

10.2 Application

Cell balancing for Ni-H_2 batteries is performed by either overcharging or reconditioning. Unlike Li-Ion batteries, Ni-H_2 batteries are more tolerant to overcharge and over-discharge. Since Ni-H_2 has a much higher self-discharge rate, trickle charging (low rate) is required to maintain Ni-H_2 battery capacity after termination of high rate charging. Trickle charge may slightly overcharge some cells but actually helps to balance the cells within a battery. It is because the highly charged Ni-H_2 cells have poorer charge acceptance and thus the SOC of the cells are somewhat equalized. Reconditioning is a process of deep discharging and recharging a battery which serves to balance cells state-of-charge within a battery. This process is commonly used in Ni-H_2 battery power system during non-eclipse season.

Lithium Ion batteries are very sensitive to overcharge and over-discharge. Overcharge and over-discharge can result in permanent damage in a short period of time. Although Li-Ion cell self-discharge rate is low, small differences in self-discharge rate between cells will cause SOC divergence over a long period of time. Therefore, cell balancing electronics are required for Lithium Ion batteries for high reliability mission.

10.3 Battery Cell Balancing Feasibility Relative to Battery Architecture

Li-Ion batteries are typically constructed in one of the architectures shown in Figure 7-2. Active cell balancing is practical for the Series and Parallel-Series architectures, due to the smaller number of cells (or virtual cells).

Cell balancing is typically not feasible in series-parallel configurations. If cells in each series string were to be actively balanced, much more electronics would be required and the system would likely be too complex. This type of battery typically uses low capacity cells (Sony 18650 type, 1-2 Ah capacity) which are screened and matched so as to minimize the cell divergence over the battery life. As a precaution against cell overcharge, an internal protection switch, or CID, will open when the overcharge protection threshold is reached. If significant cell divergence should occur, it will eventually lead to overcharge in one or more cells. If a cell in a string is overcharged, the cell CID will open and the cell string is lost. If a cell in a string is over-discharged, the cell will short and the remaining cells will eventually be overcharged, and the CID will open. Due to this possibility of string loss, the battery is typically sized to include redundant strings. Cell voltage monitoring is generally not provided due to the large quantity of cells. This type of battery is typically used in low power, shorter life mission applications.

10.4 System with No Cell Balancing

To minimize cost and complexity, some short life mission spacecraft may choose to use Li-Ion based EPS without cell balancing.

There are two options for a system with no cell balancing:

> Option 1: Use low capacity cells in series-parallel battery pack configuration. Cell balancing cannot be performed on this type of battery configuration, but cells are well matched prior to battery assembly and the battery is well protected. See details in 10.3.
>
> Option 2: Use large capacity cells without internal overcharge protection. Cell leakage currents are matched as close to each other as possible prior to battery assembly. If all cells leak rates are close to the same and the mission life is sufficiently short, cell balancing may not be required. Cells can also be balanced using ground equipment prior to battery installation in spacecraft. However, if this option is chosen, extreme care must be taken to ensure that parasitic loads such as cell voltages monitoring circuitries do not cause cell imbalance.

10.5 Cell Balancing Topologies

A few known cell balancing topologies are discussed in the following sections.

10.5.1 Shunt Balancing System

A cell balancing system which shunts excess charge current towards end of battery charging process or any other operating period is known as a shunt balancing system as shown in Figure 10-1. In this system, all cells (cells can refer to virtual cells hereafter) in series are charged at the same rate. As necessary, a switch and a shunt resistor are used to shunt excess charge current around individual cells. The balancing function is typically carried out towards the end of a charge cycle as the shunt threshold is likely set to a high SOC threshold. Or shunting can be performed periodically when a divergence threshold is reached. A commonly used process – when the first cell reaches a certain charge threshold, its associated switch will close to shunt excess charge current. The excess charge is dissipated in a resistor in series with the switch. This operation continues until the last cell reaches the same charge threshold. All shunt switches will open when the battery begins to discharge and the cell voltages fall below the charge threshold.

This shunt system requires very accurate cell voltage monitor (in the order of ~10mV accuracy), as 0.1V represents >10% of battery capacity. Cell voltage as a function of capacity is dependent on cell type and charge/discharge current. See examples in Figure 10-2. The system also requires either complex spacecraft control or high precision comparator circuits to open/close shunt switches. The magnitude of shunt current required is dependent on the self-discharge rate, battery capacity and time allowed for balancing. The shunt resistor power dissipation increases as the shunt current increases, so the thermal implications must be understood and mitigated, if necessary. A single fault tolerant system requires two sets of switches and control circuits per cell. This cell balancing scheme is commonly used in geosynchronous orbit spacecraft where there is sufficient in-sun time each orbit for the balancing circuits to completely balance the cells. For low earth orbit application, it may take many orbit cycles to completely balance all the cells in a battery.

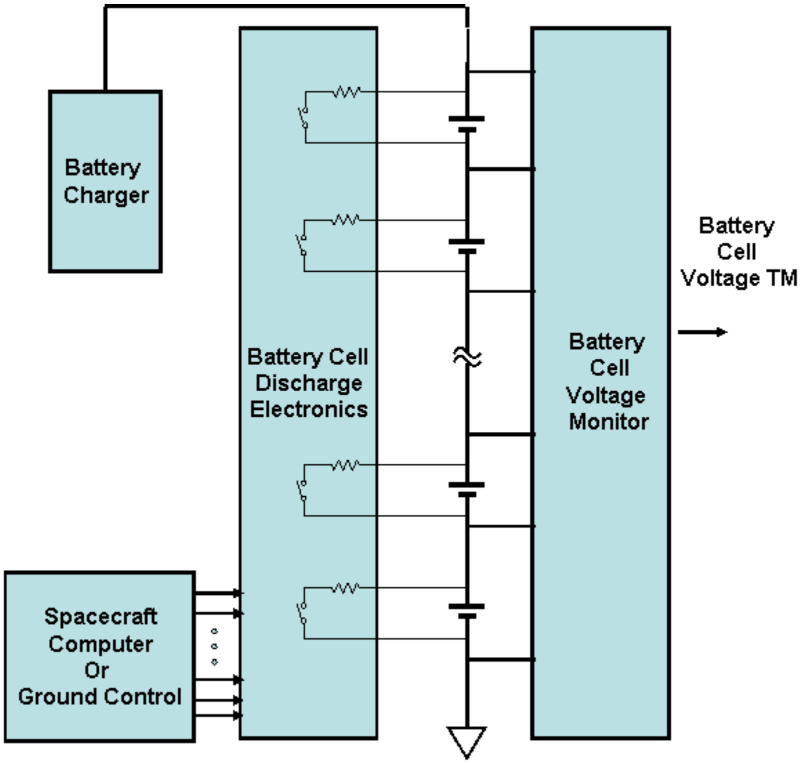

Figure 10-1. Shunt system block diagram.

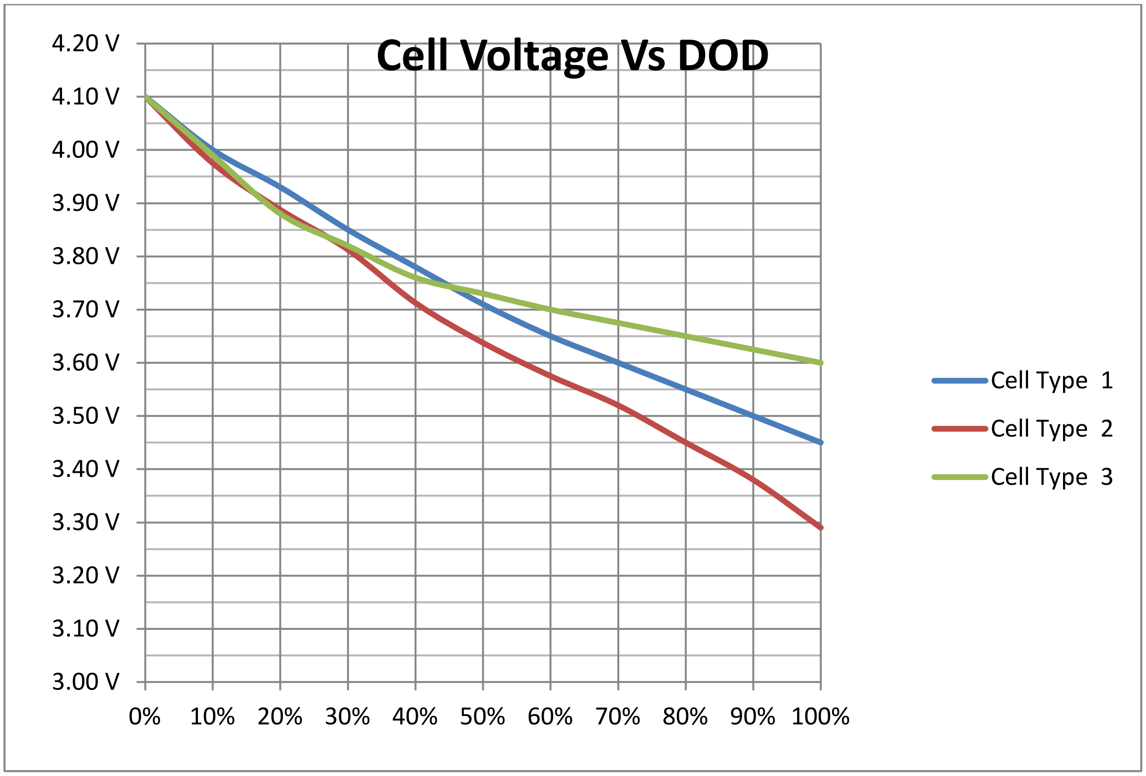

Figure 10-2. Cell open circuit voltage versus depth-of-discharge.

10.5.2 Continuous Energy Transfer Balancing System

A cell balancing system that provides continuous energy transfer between cells and does not require high precision cell voltage monitor, thus the power system design is simplified. Figure 10-3 shows a continuous energy transfer cell balancing scheme. Bi-directional transformer-coupled DC-DC converters are used for cell balancing. The primary side of each bi-directional converter is connected to a battery cell. The secondary sides of all bi-directional converters are connected together through resistors to a common node, named "shared bus." This ground-referenced shared bus voltage is equal to the average voltage of all the battery cells. The purpose of the secondary side resistor in each bidirectional converter is to limit cell balancing current. The resistor chosen has to be sufficient to compensate for the self-discharge rate of the battery. In this cell balancing scheme, the bi-directional converters allow current flowing from the higher charged cells to the shared bus and then from the shared bus to the lower charged cells, forcing all cells to be very close to equal continuously and autonomously. Power dissipation in the bi-directional converters is very low as required cell balancing current is low. In fact, the magnitude of the balancing current is proportional to the voltage difference between cells. As the cells become closer to being perfectly balanced, the balancing currents approach zero.

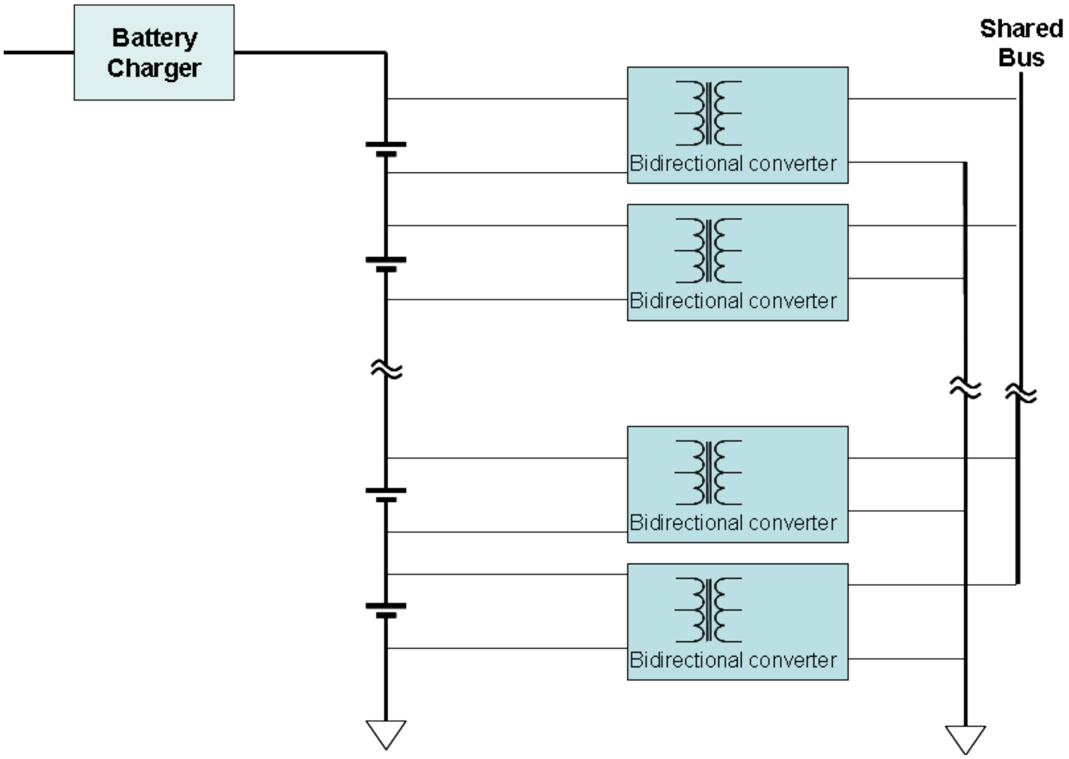

Figure 10-3. Continuous energy transfer cell balancing scheme.

A winding off the bi-directional converter transformer can provide very accurate battery cell voltage telemetry. Although accurate battery cell voltage measurements are not required for this cell balancing scheme, cell voltage telemetry is still necessary to monitor the health of the battery and satisfy range safety requirements. A single fault tolerant system requires two cell balancing converters per cell.

10.5.3 Individual Cell Charger

A power system using individual battery chargers for each cell as depicted in Figure 10-4 can also serve to balance cells. Each cell charger terminates charge when desirable charge threshold is reached resulting in balanced cells at the end of a charge cycle. This approach requires very accurate cell voltage telemetry and charge control circuit also.

Individual cell charger can be accomplished by either standalone cell charger for each cell or multiple switched outputs from a single charge controller. Individual cell chargers can be autonomous or controlled by the spacecraft processor.

A single fault tolerant system requires that the failure of a cell charger does not result in failure of the battery.

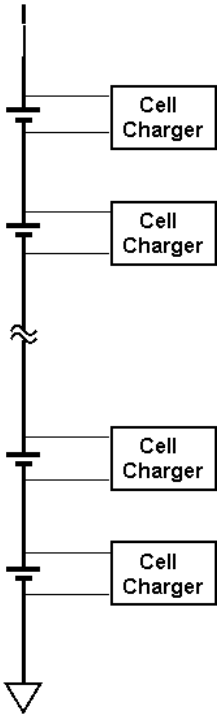

Figure 10-4. Cell balancing using individual cell charger.

10.6 Cell Balancing Topology Comparison

The following table compares the three topologies:

Table 10-1. Cell Balancing Topology Comparison

	Shunt Balancing System	**Continuous Energy Transfer System**	**Individual Cell Charger**
Complexity	Added electronics for cell balancing. External control may be required.	Added electronics for cell balancing. No external control required.	No added electronics for cell balancing, but individual cell charger adds more complexity than a central charger (for all cells in a battery).
Balancing duration	Additional duration required to balance cells at the end of charge cycle.	Continuous balancing. No additional duration required during charge cycle.	No significant added duration assuming all cells can be tapered charge to the charge termination threshold in similar durations.
Balancing accuracy	Depending on accuracy of cell voltage telemetry and comparator circuits.	Not dependent on cell voltage monitor accuracy.	Depending on accuracy of cell voltage telemetry and charge control circuits.
Orbital application	More suitable for GEO.	Can be used for all orbital applications.	Can be used for all orbital applications.
Mass	Additional mass for shunt balancing circuits, may be heavier due to added thermal mass for dissipative shunt resistors.	Additional mass for cell balancing electronics.	No additional cell balancing circuit mass, but individual cell charger power system is heavier than a central charger power system.

10.7 Unequal Parasitic Load on Battery Cells

Battery cell electronics can create unequal parasitic loads on battery cells which will automatically introduce imbalance to battery cells in a battery. For example: if ground-reference resistor dividers are used to extract battery cell voltage telemetry as shown in Figure 10-5, uneven parasitic loads are imposed on the cells. This is because currents drawn from the bottom cells in a battery is higher than that of the higher cells. Uneven parasitic loads in a Li-Ion battery should be avoided. In addition, caution should be exercised when storing a battery whose cells may be parasitically unevenly loaded. Periodic maintenance charging and/or re-balancing cells of the battery will most likely be required.

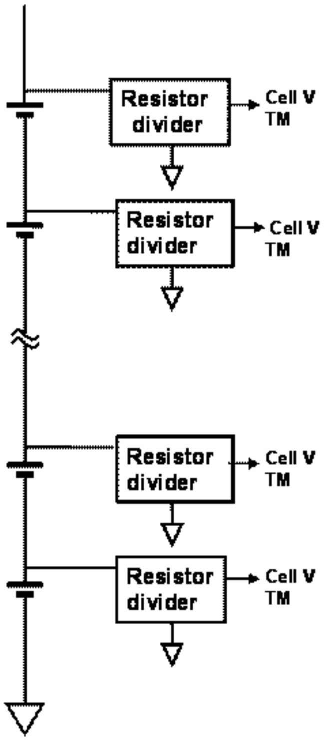

Figure 10-5. Battery with resistor divider for cell voltage telemetry.

10.8 Battery Cell Balancing Unit Integration

When a cell balancing unit is integrated with a live Li-Ion battery, the following precautions should be taken:

1) All battery cell sense lines should be fused to ensure human and hardware safety.
2) Fuse surge current should be limited during integration and test so the sense line fuses are not overstressed or blown.
3) If the cell balancing circuit is powered by the battery, ensure that each balancing circuit will power up in a known, safe state. For example the switch in the shunt balance system should stay open during power up. Note: if cell balancing circuit must be powered by the battery, current drawn from the battery should be very low and these balancing circuits should turn off when battery SOC is below a certain level or battery is off-line.

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11. Cell Bypass

Battery cell bypass function provides an alternate high current path for battery charge and discharge around a failed battery cell. The purpose of cell bypass is to avoid a single point failure in a battery. Cell bypass afford a means to lower the risks associated with loss of a battery (often, loss of a mission). However, some systems or missions may have higher risk posture, redundant batteries, or short mission durations, all of which could preclude the need for cell bypass functionality.

11.1 Cell Failures

Li-Ion battery cells can fail open or short. See section 7.1.5 for details of these potential cell failures. By having the capability to bypass a failed cell or failed virtual cell, the reliability of a battery is typically improved. However, it should be noted that unless there is a means of replacing the bypassed cell with a spare cell, the battery will operate at a lower voltage and lower energy storage capability after a cell has been bypassed.

11.2 Battery Cell Bypass Feasibility Relative to Battery Architecture

There are three different Li-Ion battery architectures – cells can be connected in series, series-parallel or parallel-series. See Figure 7-2.

For a series connected battery, a single cell failing open will result in immediate failure of the battery unless a cell bypass function provides a current path around the failed cell.

For a series-parallel connected battery using 18650 type small cells, cell-bypass capability is not included. It is neither necessary nor practical to add so many cell-bypass circuits. Any single cell failing open will lead to the loss of one cell string. Any single cell failing short will eventually lead to cell overcharge in this string. Should that happen, the cell internal overcharge protection circuit will open and this cell string will be detached from the battery. Cell string redundancy will allow the battery to continue to provide the required capacity.

For a parallel-series connected battery, a single cell failing open in a virtual cell may not cause any immediate failure. Depending on the number of cells in the virtual cell, the remaining healthy cells may fail due to overcharge or over-discharge. This could result in loss of battery since the higher capacity cells typically do not have internal overcharge protection. Therefore, individual cell voltage monitor is essential to detect the failure and cell by-pass is required to remove this failed cell from the battery.

A single cell failing soft short in a virtual cell should not pose any threat to the safety of the battery. A hard short may cause a catastrophic failure due to the immediate high discharge of the other parallel cells, but this type of failure is deemed to be extreme unlikely. Since the resistance of a failed cell cannot be defined, cell bypass is a desirable feature to maintain a low impedance battery.

11.3 System with No Cell Bypass Capability

Adding cell bypass capabilities adds complexity to battery and battery electronics. Systems using higher capacity cells with lower reliability mission or redundant batteries may choose not to have cell bypass capability.

11.4 Cell Bypass Schemes

Two known schemes have been used for cell bypass. The subsections below describe these schemes.

11.4.1 Cell Bypass Switch

A cell bypass switch scheme shorts the failed cell when the cell SOC is low or driven into reversal as shown in Figure 11-1. When this failure is detected, the switch can be closed by command or autonomously to create a low-impedance path electrically in parallel with the failed cell. In this scheme, shorting a highly energized cell can cause a cell to overheat and vent so a two-fault tolerant design should be implemented.

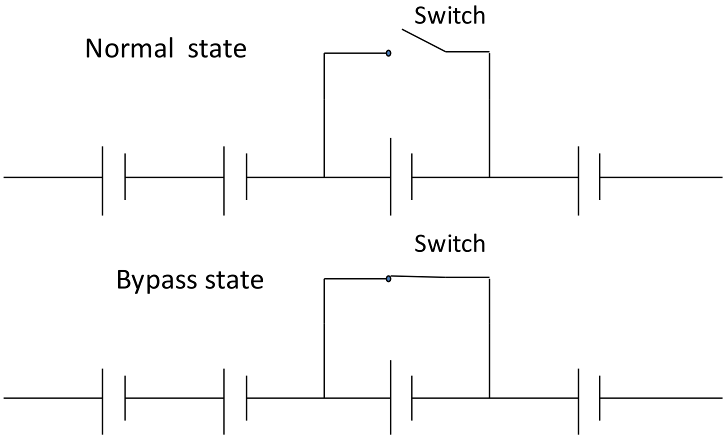

Figure 11-1. Cell bypass switch scheme.

11.4.2 Cell Isolation Switch

A cell isolation switch scheme provides an alternate low impedance path around a cell as shown in Figure 11-2. The switch is designed to provide a make before break transition during actuation. Once actuated the cell is isolated from the electrical circuit. The cell isolation switch is safer than the cell bypass switch as under normal operation there is no concern of accidentally shorting a highly energized cell.

11.5 Autonomous Versus Commanded Cell Bypass

Autonomous or commanded cell bypass for Li-Ion battery power system can be used as long as mission reliability is met and safety concerns are mitigated.

11.6 Resettable Versus Non-Resettable Cell Bypass

After a Li-Ion battery cell is shorted, it will become permanent short so resetting the bypass switch serves no purpose. The cell isolation switch is a one-shot circuit and not resettable.

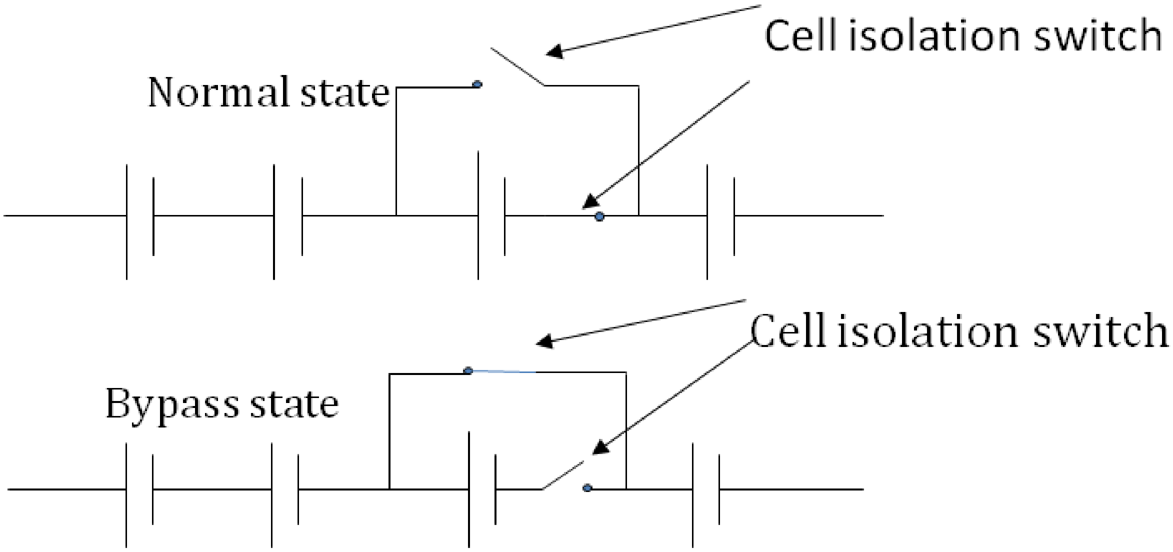

Figure 11-2. Cell isolation switch scheme.

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12. Depleted Battery Prevention and Maintenance

All solar power based electrical power systems rely on a secondary battery to provide electrical power during normal eclipse periods. Highly reliable power systems may also depend on the battery to supply power for off-nominal conditions such as loss of solar array pointing capability. However, the battery cannot provide power indefinitely. In the event of a spacecraft anomaly that causes less than normal solar insolation the battery may over-discharge to the point where it suffers a permanent loss of capacity. This section describes methods to prevent battery damage due to over-discharge, and suggests necessary features of a system designed to maintain battery health if the battery is disconnected. Although the discussion assumes a single battery system, the same principles apply to multiple battery systems.

12.1 Design Considerations

12.1.1 Tiered Safe Mode Response

Many modern spacecraft rely on a computer processor to initiate a safe mode response triggered by low battery SOC. These systems may also be capable of anticipating conditions that will result in low battery SOC and take corrective action to prevent this condition. Typically the safe mode response will include some combination of load shedding and sun search. Reducing the spacecraft load and optimizing solar insolation will protect the spacecraft bus from a potentially unrecoverable dead bus condition.

A tiered safe mode response refers to the order in which loads are removed and sun search algorithms are implemented. The order is dependent on a risk assessment that weighs the chance of system survival against the complications of re-establishing normal spacecraft command and control. For example, it may be very beneficial from a power standpoint to turn off non-critical payload units. Doing so may restore enough power to prevent the need to turn off critical heaters and communication units. However, the decision to turn off critical propulsion system heaters must be weighed against the probability of frozen and burst fuel lines.

The order in which units are turned off may be similar to this:

1) Payload units
2) Non-critical heaters
3) Critical heaters (such as propulsion system heaters)
4) Other critical units.

In general, the order in which units are turned off is determined by some measure of battery SOC. For Li-Ion batteries, the simplest indicator of battery SOC is battery voltage. Load shedding may be controlled by the spacecraft processor, or may be controlled by electronic sensors.

12.1.2 Post Safe Mode Operation

Through some unforeseen failure, the battery may continue to discharge due to an unsuccessful safe mode response. In this case it may be necessary to reduce or inhibit continued battery discharge to prevent permanent damage to the battery and the subsequent loss of mission. Further battery discharging can be prevented by interrupting the battery discharge path with a switch, such as a relay or MOSFET, or by disabling the battery discharge controller(s). The battery cannot be completely disconnected; the system must retain the capability to charge the battery. Figures 12-1 and 12-2 show two possible implementations of this concept.

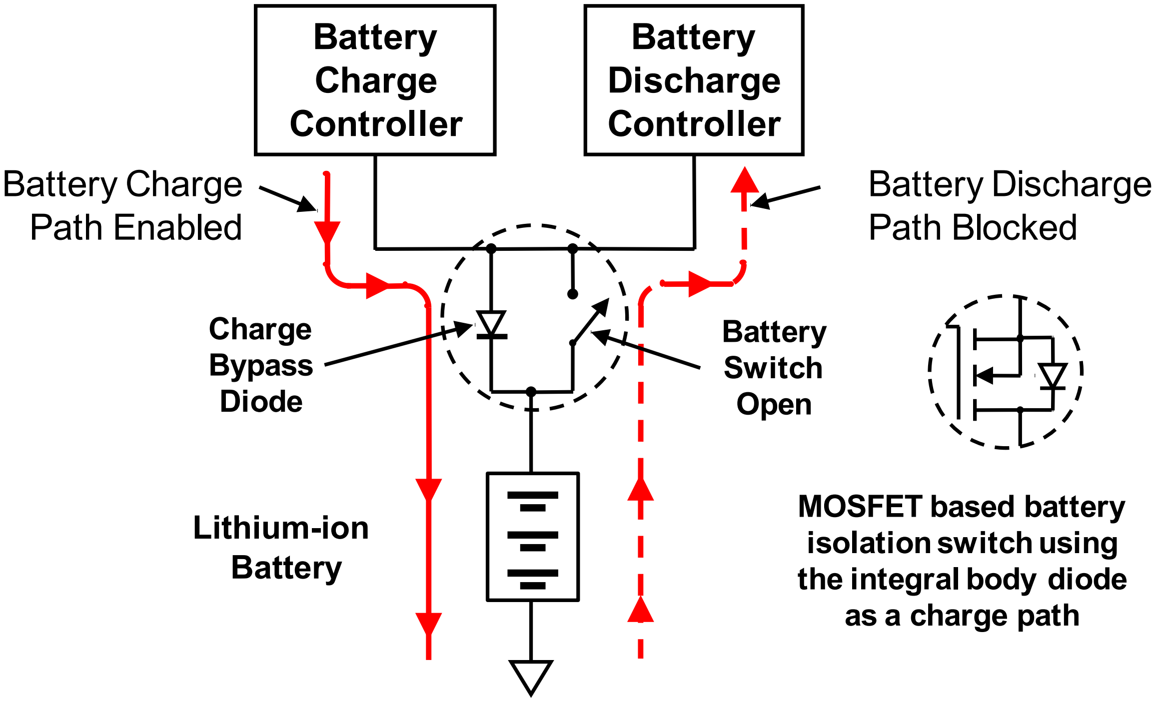


Figure 12-1. In-line battery isolation switch.

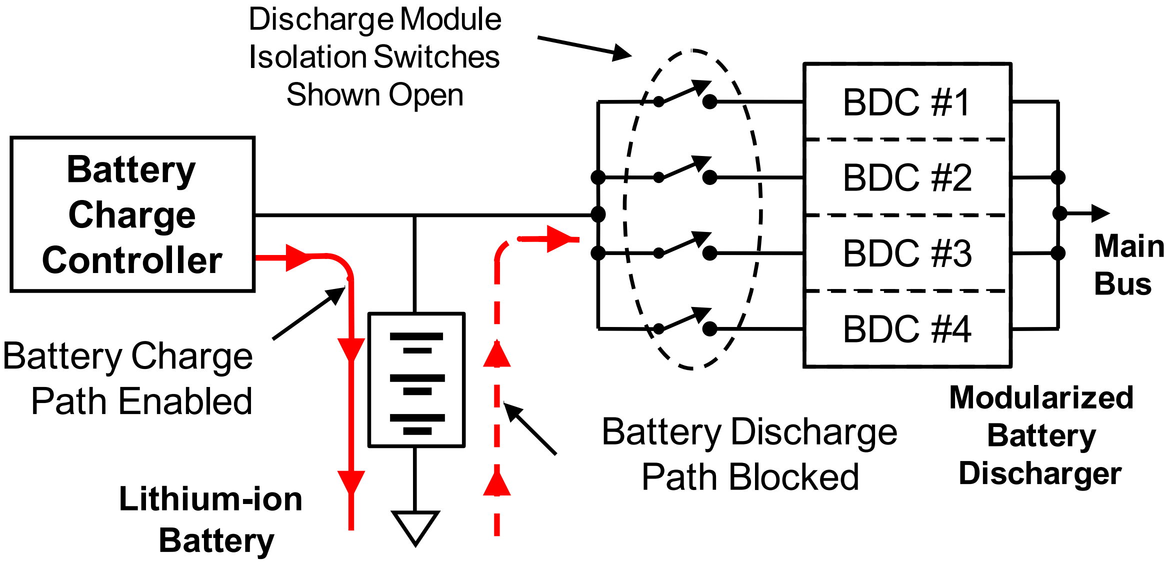


Figure 12-2. Modularized battery isolation switch.

One must consider the point at which to disconnect the battery discharge path. Sufficient time must be allowed for the sun search algorithm to restore suitable solar isolation; the probability of success for this action increases with time. Disconnecting the battery before the sun search algorithm is complete will prevent sun acquisition and virtually guarantee a dead bus.

Disconnecting the battery while the battery is discharging will result in a dead bus condition. This will result in the temporary, possibly long term, loss of spacecraft telemetry, command and control. It will also result in the loss of heater power to all spacecraft components including all payload units, critical bus units, propulsion system elements and batteries. Recovery from a dead bus condition cannot be guaranteed. Even if the dead bus is restored to normal, spacecraft components may be damaged or destroyed due to freezing.

Prior to disconnecting the battery it is desirable to configure certain functions for future use. After disconnecting the battery it is critical to ration solar array power in order to keep the battery warm, recharge the battery and restore command and control. This is more likely to be successful if all heaters, except battery heaters, are disabled before disconnecting the battery. All loads should be disabled except those required for recovery. Any parasitic battery loads, such as cell balancing, should also be disabled. Before disconnecting the battery it may be useful to configure the spacecraft processor and other critical units required for recovery. Also, all extraneous units which may “boot up” autonomously upon restoration of bus power should be disabled.

12.1.3 Battery SOC Disconnect Threshold

When selecting the optimal SOC threshold at which to disconnect the battery, consideration must be given to the normal range of battery operation. Obviously, the battery disconnect threshold must be lower than the minimum predicted SOC during normal operations. Also, the threshold SOC should allow time for other safe mode responses to achieve success. Ultimately, if the battery is disconnected it should be disconnected at a safe storage voltage.

Battery voltage offers the simplest indication of SOC for Li-Ion batteries. However, battery voltage is also affected by battery current, internal cell resistance, and temperature. It is important that the voltage detection system account for normal battery voltage transients due to pulse loads, fault clearing events, and sensor noise. Voltage telemetry persistence schemes, current and temperature compensation, and resistive-capacitive circuit filtering methods may be required to prevent false trips.

Ideally, the threshold at which the battery is ultimately disconnected is a parameter value that can be changed by ground command. If total battery voltage is used to determine when to disconnect the battery, it may be necessary to command a new threshold value if there are one or more battery cell failures that cause a reduction in the normal battery voltage.

12.1.4 Disconnect Switch Considerations

The battery (or batteries) is normally connected to the bus, battery discharge regulators, charge regulators and other circuits, through one or more disconnect switches. In most cases, these switches are mechanical latching relays. The battery disconnect system may use these switches or a separate set of switches for the battery disconnect function.

The battery switch or switches are most likely connected in a high-current path containing resistive, inductive, and capacitive elements. Special consideration must be given to the series inductance, especially when opening the switch under high current and high battery voltage conditions. Whether relays or high power MOSFET switches are used as a disconnect device, the switch must be able to open without exceeding the device voltage, energy, and current ratings.

For a battery dominated bus, a means must be provided to prevent the solar array from being connected directly to the bus while the battery is disconnected. Since the battery is what normally controls the bus voltage, in the absence of the battery, the bus will move towards the open circuit voltage of the solar array should insolation be restored with the array connected to the bus. This voltage will normally be well in excess of the maximum steady state and transient input voltage that the loads are designed for, and will potentially lead to catastrophic damage to the loads.

Alternately, for a battery dominated bus, the solar array regulator must be capable of independently limiting the bus voltage to a safe level if the batteries are not connected.

12.2 Disconnected Battery Maintenance

While disconnected, the battery must be maintained in a safe state if it is to be re-connected to the power system after solar insolation conditions improve. As a minimum, a set of electronics and controls is required to

1) Control battery heaters,
2) Control battery charging, and
3) Reconnect the battery to the EPS.

These functions may reside in a dedicated assembly, or may be distributed throughout the power system electronics and spacecraft controllers. These battery maintenance functions are operated to the extent that incidental solar array power is available.

After the battery is disconnected it may be impossible to control battery temperature or to prevent the battery from freezing. Unlike Ni-H2 systems, it is not possible to effectively charge a Li-Ion battery while it is frozen. When very cold or frozen the battery acts as a high impedance load, even low charge current into the battery will cause a large increase in battery voltage without achieving any significant increase in SOC. The battery charger must be inhibited from charging until all battery cells are at a temperature where it is safe and effective to do so.

The battery maintenance electronics should be designed to manage two conflicting operating goals. One goal is to keep the battery from freezing, or to thaw the battery before charging. The second goal is to charge the battery. Ideally, the battery maintenance electronics would first use any excess solar array power to warm the battery to a usable temperature, and then charge the battery with any additional power. In a simple implementation, a thermostatically controlled switch may be used to control battery heater power and another thermostatically controlled switch may either inhibit or allow battery charging based on battery temperature.

The battery maintenance electronics must be capable of charging the battery while it is disconnected from the spacecraft loads or battery discharge regulator. The battery charge circuit may be separate from the normal battery charger. In fact, a failure of the primary battery charger may have been the cause of the low battery SOC that precipitated the disconnect event. In any case, the battery charger should use available solar array power to charge the battery while preventing battery from discharging.

The battery maintenance electronics should not be allowed to charge the battery if the battery temperature exceeds a safe threshold.

Operating battery heater switches through a scheme that turns the heaters ON or OFF based on battery temperature may result in bus voltage “motor boating.” That is, the bus voltage may rise as the solar array illumination increases, then collapse to a low voltage when the heater switch turns ON. When the heater switch turns OFF, the bus voltage may then rise again. This same phenomenon may occur when switching on the battery charger. Ideally, both heater control and battery charge control will sense the available solar array current and adjust their outputs in order to maintain high bus voltage and efficient use of the solar array power. Although bus voltage oscillation may be unavoidable, it should be anticipated and should be considered when designing power electronics circuits which may be damaged when operated under low voltage conditions. The motor boating conditions will diminish as more solar array power becomes available.

12.3 Bus Architecture Considerations for Battery Maintenance

With sunlight-regulated and fully-regulated bus architectures the bus voltage should restore to normal once sufficient solar array illumination is achieved. In this case, telemetry and command capability may be restored as well, at least for the duration of the illumination. Once a minimum set of critical loads is powered, any excess solar array power should be used to heat and charge the battery and prepare for reconnection.

For systems employing a battery dominated primary bus, the solar array regulator must have the capability of independently maintaining bus voltage regulation once insolation is restored, otherwise it will be necessary to provide an auxiliary bus powered from the solar array while the solar array is disconnected from the primary bus. This auxiliary bus is used to power the battery maintenance electronics, provide both heater power and charge current to the battery, and to power the circuitry required to reconnect the battery to the primary bus once the proper conditions are met.

For systems that use series switches to connect the solar array to the primary bus, a bootstrap supply derived off the solar array is required in order to power any circuitry that is required to reconnect the switches to the primary bus once insolation is restored. In the case of a battery dominated bus, this can be the same auxiliary bus used to power the battery maintenance electronics.

12.3.1 Battery Reconnect, Hardware Considerations

At some point, it may be desirable to reconnect the battery and begin spacecraft recovery. This operation may be autonomous, or may require ground commands. In either case, several conditions should be assessed before closing the battery switches.

1) The battery must be at a sufficiently high SOC. The SOC must be high enough to support the recovery process, including any predictable eclipse intervals.
2) The differential voltage across the battery switch must be low enough to prevent damage to the switch due to current inrush and/or relay contact bounce.
3) The battery temperature must be high enough to prevent a high impedance battery condition that will manifest itself in low voltage during discharge or high voltage during charge.

The hardware design should include features that prevent reconnection of the battery unless the above conditions are all met. It is recommended that the battery maintenance electronics be disabled after the battery is connected in order to prevent interference with the normal battery charge control process.

12.4 Reliability Considerations

The battery disconnect system must be at least single fault tolerant against inadvertent activation. Disconnecting the battery during most operational phases could result in mission failure. Good design practice requires that no single part failure, errant command, short circuit, or open results in opening the battery switches. Activation of the battery disconnect switch should be based on a combination of independent voltage detection circuits, commands or other signals that vote to initiate the battery disconnection. Even though battery disconnect function must be single fault tolerant to inadvertent disconnect, the disconnect function itself does not need to be redundant. Also, the battery maintenance and reconnect functions also need not be redundant.

12.4.1 Test and Operations Considerations

The battery disconnect function and the battery maintenance and re-connect functions should be tested at both the unit and integrated system level. Special consideration should be given to the fact that the bus voltage may collapse if the battery is disconnected from the system. Other spacecraft units should be designed to withstand the voltage transients that can be generated when the battery is disconnected or reconnected. Momentum wheels and reaction wheels may generate excessive bus voltage transients if they spin down while the battery is disconnected from the bus.

Activating the disconnect switch may place high stress on the switching components (relays and/or MOSFETs). It may be desirable to perform a limited number of qualification tests to demonstrate the high current capability of the switch. However, for routine testing it is sufficient to demonstrate the functional operation of the circuits by operating at lower current levels.

13. Recovery from a Dead Bus Condition

13.1 Power Outage Interval

13.1.1 Assumptions

The exact state of the spacecraft during the power outage interval will depend on the particular way in which the battery protection and recovery scheme has been implemented. For this discussion, the following conditions will be assumed:

a. All loads have been shed with the exception of only a minimum set of essential equipment required for bus recovery such as transponders and command receivers. Any loads that cannot be disconnected, such as survival heaters with bimetallic thermostatic control, will place a burden on available solar array power during the recovery phase, lessening the chance of, or preventing a successful recovery.

b. Battery discharge has been disabled, either by disconnecting the battery outright (the preferred method), or some other means of severely restricting discharge current to an acceptably low parasitic level.

c. Battery recovery heaters are enabled. The battery recovery heaters may consist of the normal battery heaters; however, it is assumed that during recovery the heaters are independently controlled by the recovery electronics.

d. The battery recovery electronic subsystem has been designed to autonomously recharge the battery using whatever solar array current is available. The amount of charge current available depends on the nature of the anomaly and whether it resulted in an unfavorable sun attitude on the arrays. If the vehicle is in a tumble or flat spin, the time profile of available solar power may be highly irregular as shown in Figure 13-1. The charging system must be able to accommodate whatever power profile is available and supply whatever it can to recharge the battery while it is off-line. If the normal battery chargers are not inherently single fault tolerant, an alternate means of charging the battery is recommended in case the low SOC is caused by a failed charger. Autonomous vs. ground command enabled battery charging is discussed below.

e. Telemetry from the vehicle is unavailable. There may be cases, depending on the particular system and how it is designed, that some telemetry may be available; if there is, it could affect the recovery approach as discussed later.

f. A means exists to reconnect the battery once the battery voltage has increased to an appropriate threshold. Whether this should be done autonomously or via ground control will be discussed below.

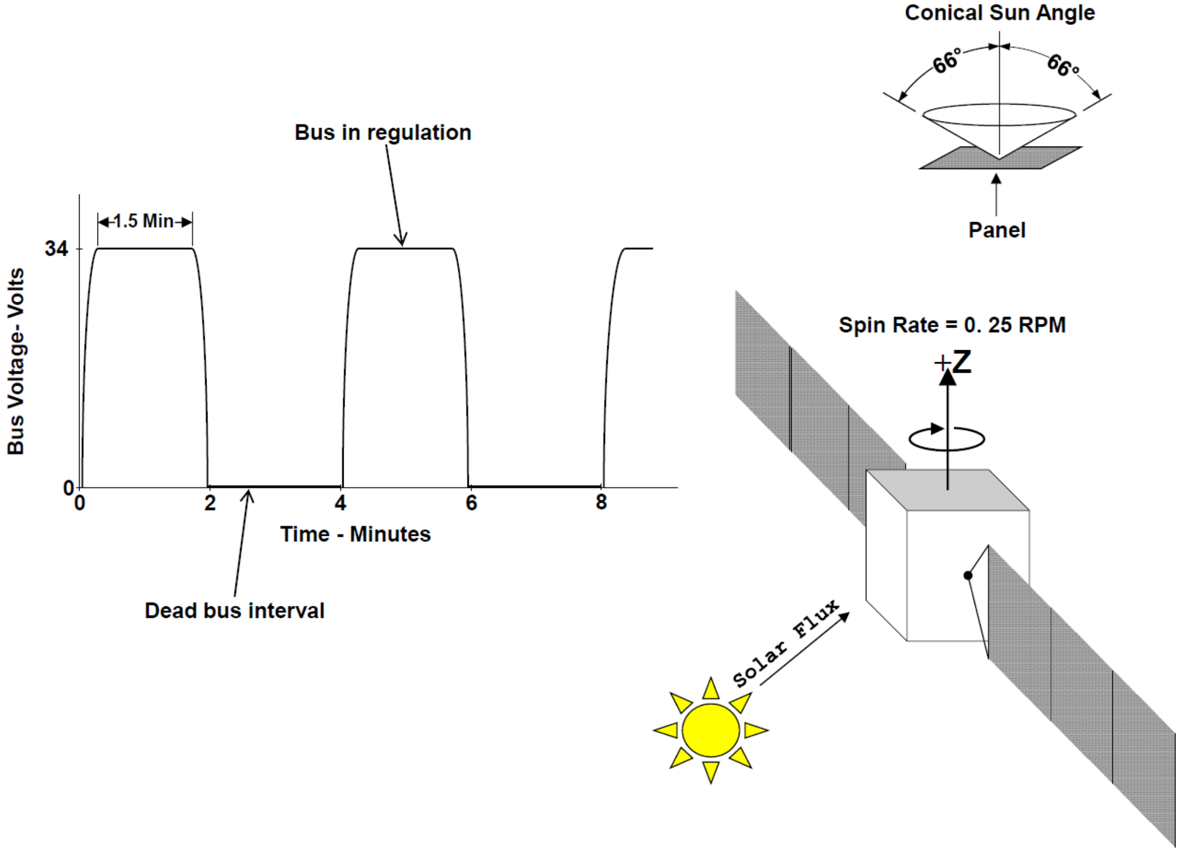
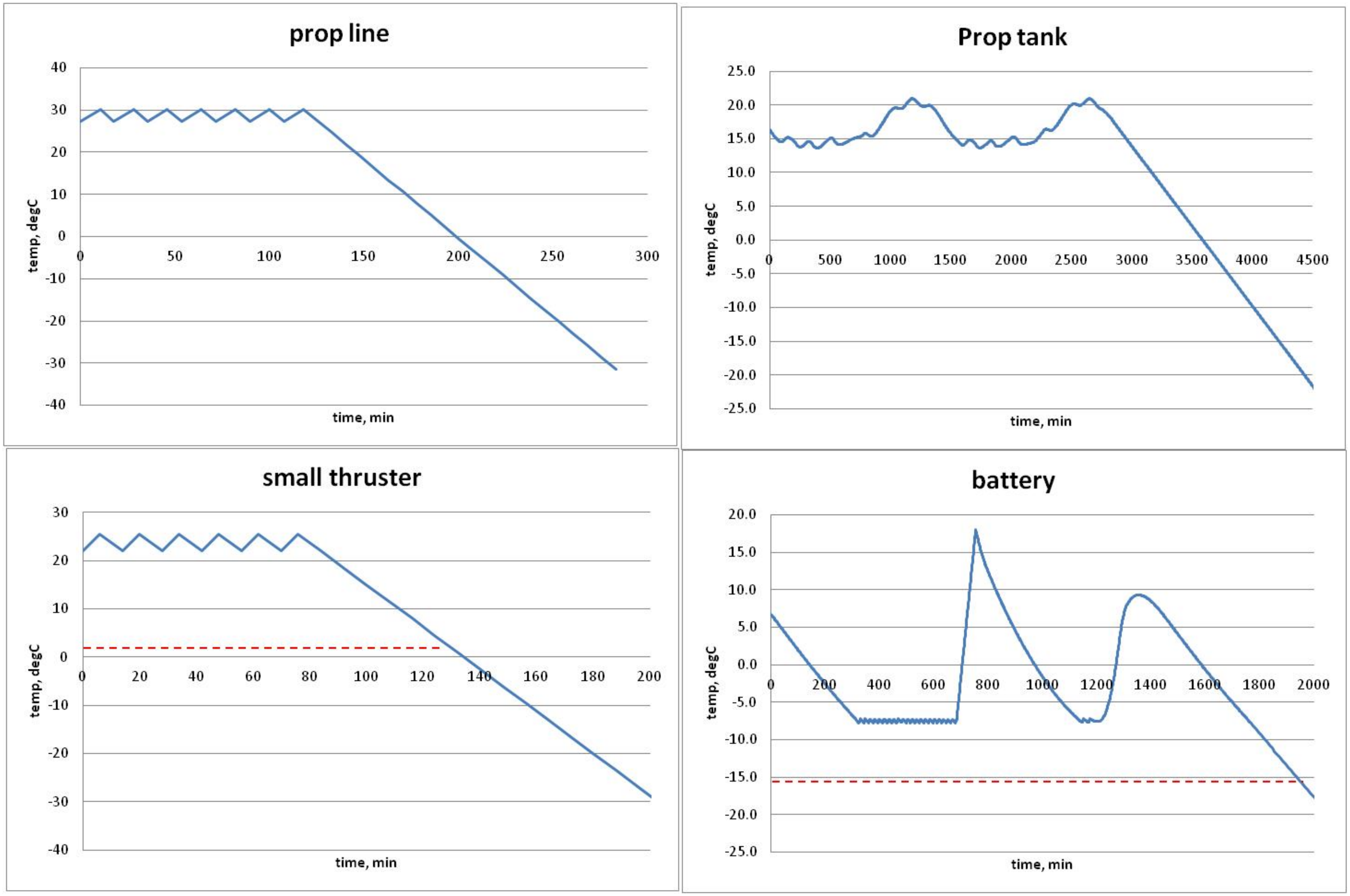


Figure 13-1. Intermittent power of a spacecraft tumbling at 0.25 rpm.

13.1.2 Spacecraft Temperatures

During the power outage interval, temperatures through the spacecraft will fall. For any particular component, the rate of temperature decrease depends on the thermal mass and the thermal conductivities to other components as well as radiated emissivitiy and view factors to other components or to space.

Propulsion lines and small thrusters have low mass and therefore become cold quickly, freezing the propellant in the lines as shown for a typical case in Figure 13-2. Propellant tanks take longer to become cold enough for their contents to freeze, but given enough time off of heaters, eventually all the propellant will freeze. But although temperatures may go far below the qualification temperature range of the propulsion subsystem, there is a good chance of recovery if warming of the tanks, lines, and valves is handled appropriately after restoration of electrical power. To prevent ruptures, thrusters should never be autonomously enabled during the recovery interval.


prop line

Prop tank

small thruster

battery

Figure 13-2. Typical rate of temperature decline (right-most portions of the plots) of propellant lines, tanks, thrusters and batteries for a typical large satellite, when all heater power is removed, as might be the case after battery disconnect.

13.1.3 Spacecraft Attitude

Loss of attitude control of the spacecraft can result in loss of available power from the solar arrays and rapid depletion of the spacecraft batteries. The spacecraft could conceivably be in a slow roll, if attitude control were lost due to a gradual loss of energy in momentum wheels, or in a rapid tumble or spin, if an anomaly resulted in loss of control of energetic momentum wheels, causing a rapid dumping of angular momentum to the spacecraft. Rotation might be largely confined to one spacecraft axis, or there could be simultaneous rotation about other axes, resulting in anything from a mild wobble to a chaotic tumble about all three axes.

The time profile of available solar power depends not only on the type of tumble or spin, but also on the solar array configuration. If the arrays are coplanar, as is typical for sun-tracking wing designs, there will only be power as the array normal vector passes through the neighborhood of the sun vector. As array power varies as the cosine of the angle between the array normal and sun vectors, there is a significant drop-off of power as this angle increases.

Spacecraft that have non-coplanar body-mounted solar panels (perhaps canted at various angles or mounted on different spacecraft faces), will have available solar power over a larger portion of the tumble or spin period, although the peak power available will be less than for a coplanar design of identical total array area.

For a tumbling or spinning spacecraft the period coupled with the percentage of that period with significant array power influences the ability to send commands to the spacecraft. Even if the transponders are designed to give full 4π-steradian coverage, there may be difficulty in receiving commands if the effective “duty cycle” of sufficient bus power in sunlight to operate the transponder is severely limited. Likewise, a very high rate of spin or high degree of wobble could conceivably degrade the ability to receive commands. Such factors should be studied during system design, especially if ground rather than autonomous control during recovery operations is envisioned. Another aspect of vehicle attitude to consider is that of the natural spin axis of the spacecraft. Spacecraft generally have a natural spin axis that will eventually dominate rotational motion when a total loss of attitude control occurs. If this axis happens to be in a very unfavorable orientation relative to the sun vector, it may be that very little sun will reach the arrays. The spacecraft will go into a deep freeze until the sun attitude improves due to seasonal beta angle variation (limited to ±23 degrees for GEO, and non-existent for sun-synchronous orbits). Fortunately, even with a small amount of available insolation, it should be possible to recharge a completely load-free Li-Ion battery in a reasonable period of time. If autonomous reconnect is available, the spacecraft bus will come up, and the command receiver will be ready to receive commands to begin warming the propellant lines and attempt attitude recovery.

13.1.4 Ground Control Resources

The type of orbit determines how relevant ground control resources are to recovery of a spacecraft that has experienced activation of its DBP function. For an on-station GEO mission, the spacecraft is always in view, and there is a high probability of receiving commands from the ground. The only uncertainty would be in a high-rate tumble or wobble scenario, when the transponders might have difficulty accepting commands.

Every GEO mission must first be launched, and it is during ascent and orbit-raising that the risk is highest of a negative energy-balance situation that might lead to tripping the DBP function. Solar arrays are generally folded, allowing only a relatively small array area to power the vehicle. Power margin during this phase of the mission is often very small. A tumble upon launch vehicle separation or becoming stuck in a tip attitude prior to a burn are examples of the ways in which a negative energy-balance situation may arise. In a LEO park orbit for a GEO mission, contact windows are generally fairly long, and depending on the types of ground resources that are engaged in the mission, the risk of being out-of-contact while attempting to recover the vehicle is fairly low. Still, such considerations should be included in the decision whether to use ground or autonomous DBP reconnect.

13.2 Recovery Approaches

13.2.1 Autonomous vs. Ground-Commanded Battery Reconnect

The issue of whether battery reconnect should be autonomous or commanded from the ground involves many factors. The main factors are as follows:

1. Off-line battery recharge and thermal management – As discussed above, during the recovery interval, when the available solar array power is sufficient to power the essential bus loads, any excess power may be used to recover and recharge the batteries with the priority first given to ensuring that the batteries are warmed to a safe-to-charge temperature. At some threshold voltage, as depicted in Figure 13-3, there will be sufficient energy in the batteries to attempt a recovery. This threshold may be a predetermined amount, monitored autonomously, or if battery voltage telemetry is available, ground controllers may send a command to recover the batteries. The advantage to a fully autonomous recovery is that it eliminates second-guessing by ground personnel who may decide to terminate recharge prematurely, not leaving sufficient time to give the best chance of recovery. The threshold recharge voltage should be sufficient to allow adequate time for recovery, but of course, this must be balanced against the fact that temperatures throughout the vehicle are dropping while the bus is dead.

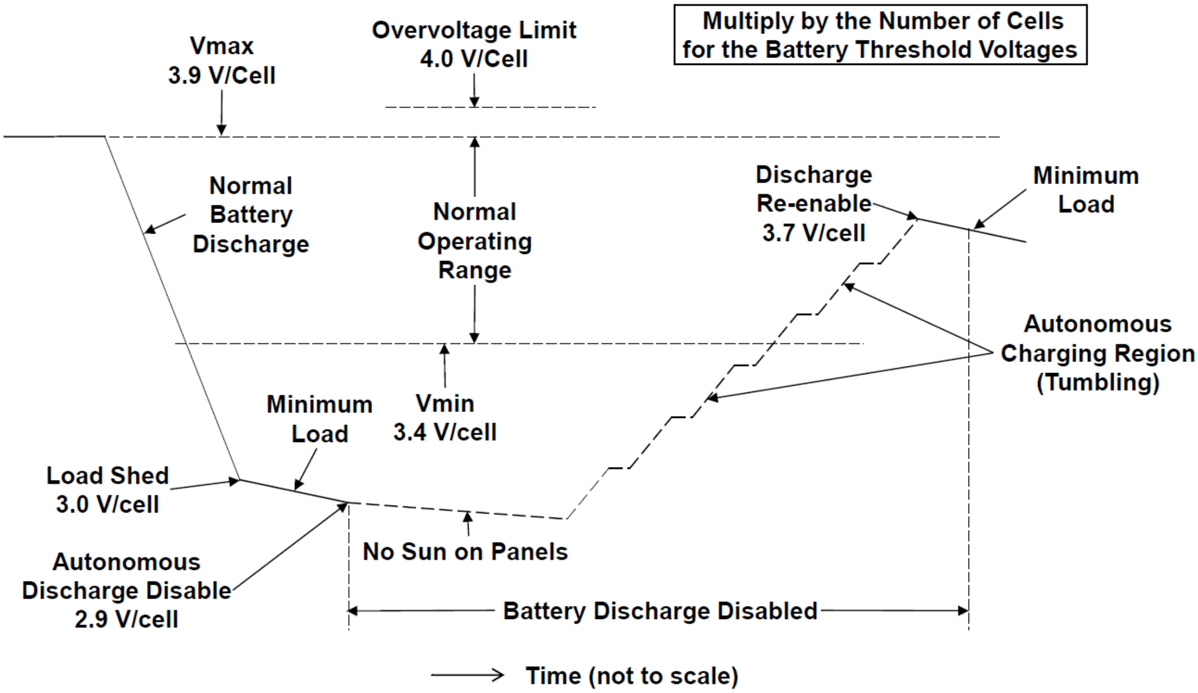


Figure 13-3. Typical Li-Ion cell threshold voltage levels.

An advantage of ground-controlled reconnect is that all available information may be assessed in real time, allowing the Flight Director to make the most informed decision possible. The downside is that there may be very limited telemetry on which to base such decisions.

2. Discontinuation of off-line charging and re-enabling of battery discharge capability – Once the predetermined threshold voltage is reached, the battery can be reconnected. Depending on what type of switching device is used, this may not be as simple as just throwing a relay switch. Switching the large inrush current that can result from switching a battery into discharged capacitors can result in permanent damage to the switching device or permanent welding of relay contracts. Before reconnecting the battery, the differential voltage across the switching device must be sufficiently small to keep the resulting inrush current below a safe level. The means of achieving a safe battery reconnect should be designed into the hardware, whether autonomous or ground command is desired. If the reconnect is done autonomously, hardware constraints must be in place to ensure a safe reconnect. If ground reconnect is desired, the same hardware constraints must be in place. As an example, the battery reconnect constraints should preclude battery reconnect unless:
    1) the battery is above the minimum operational temperature
    2) the battery has been sufficiently recharged
    3) the differential voltage across the connect switch is below the safe to connect threshold.

3. Orbital considerations – The spacecraft orbit type plays a role in the decision whether to have ground vs. autonomous reconnect. With a GEO orbit, there is at all times a direct line of sight to the spacecraft, which means that commanding is generally very reliable (with the possible exception of a rapidly spinning or tumbling vehicle). A LEO orbit, on the other hand, depending on the inclination, may have limited contact windows with ground stations. This discontinuity in commanding opportunities may make autonomous reconnect a better choice.

13.2.2 Steps to Full Vehicle Recovery

After successful reconnection of the recharged battery, an orderly re-establishment of spacecraft functions must be undertaken. Depending on how the system is designed, these steps to be taken may be done autonomously or via ground command. The required functions could be grouped into a "recovery macro" and executed either autonomously or in response to a single ground command, or there may be multiple recovery macros, each of which might be commanded separately. This implies, of course, that all the right "hooks" have been designed into the flight hardware and software, and that appropriate ground commanding schemes have been formulated and tested during the development phase of the program.

1. Resumption of telemetry – it is important to re-establish telemetry upon battery reconnect. There should be a dedicated mode that provides detailed EPDS, ADCS, thermal, and on-board-computer telemetry adequate for troubleshooting purposes. Ideally, it should be possible to receive telemetry independently of whether the onboard computer is operational or not, but this is architecture-dependent.
2. Re-enabling of survival heaters – ideally, reconnection of survival heaters would be carried out in a targeted fashion, such that essential pieces of equipment or equipment zones could be warmed sufficiently to attempt vehicle recovery while consuming the least overall amount of electrical power. However, some systems may not allow this level of control, and it may be necessary to re-enable all survival heaters.

3. Rebooting of onboard computers and resetting of command receivers/cryptos to default state – the resetting of command receivers and cryptos must be ensured by design; otherwise, it might be impossible during the recovery attempt to send an authenticated command to reset them (i.e., a lockout condition). Assuming that commands can get in, rebooting of the onboard computer may be attempted. In some systems, the computer will reboot automatically when power is provided. Other systems may require a ground command. If commandable, and if telemetry is available independent of the onboard computer, the telemetry should be assessed prior to attempting a computer reboot. Where possible the backup onboard computer should be enabled instead of the primary computer, in case the problem that caused the dead bus was due to a hardware fault on the primary side or in the "toggle" mechanism that should have caused automatic switchover failed to.

   If the onboard computer reboots successfully, it should automatically transition to safe mode and initiate a sun-search. It is presumed that the Fault Management Software (FMS) will be active. However, if the cause of the dead bus was due to some logic flaw within the FMS itself, and if the same conditions still exist upon restarting FMS, it is conceivable that the FMS would respond in the same unfavorable way. Therefore, ground controllers should be prepared to disable the FMS should this happen.

4. Thawing of propulsion subsystem elements – the restoration of vehicle attitude control is a critical part of the recovery process. Depending on how long the vehicle has been without power prior to reconnection of the batteries (after off-line charging is complete), it may take significant power and a significant amount of time to thaw the tanks and propellant lines so that the thrusters could be operated. Alternate means of restoring and maintaining attitude control such as the reaction wheels, electric thrusters, or torque rods should be used during the initial recovery phase.

5. Reconfiguration of ADC subsystem sensors and actuators – this would usually take place as part of entry into safe mode. It is highly recommended that redundant or dissimilar preconfigured sensors and actuators be used, as it is possible that a fault in one of the primary sensors or actuators may have been the cause of the dead bus in the first place.

6. Achieving Safe Mode – assuming the onboard processor is successfully rebooted, entry into safe mode should be automatic. If safe mode entry is unsuccessful, then as mentioned above, it may indicate a problem with the onboard computer or the FMS. Commanding a switchover to the redundant OBC, or disabling FMS, may solve the problem. If safe mode cannot be achieved with either OBC, regardless of whether FMS is enabled or not, this would indicate a pernicious fault mode of some kind, either in hardware or in software. Recovery may not be possible in such a scenario.

7. Attitude Restoration – provided that safe mode can be attained, and given that redundant sensors and actuators are used, and given that the propulsion system can be thawed and used, or alternatively reaction wheels, then it is likely that sun acquisition can be achieved. Once this sun-safe attitude is achieved, then the process of determining root cause and developing a path back to normal operations can be undertaken in a less time-constrained fashion.

Safe mode should have the capability to access and downlink historical telemetry data to assist in the root cause determination. This should include last-known (i.e., before the anomaly) configuration data, as well as EPDS data, temperatures, commanding history, attitude parameters, ADCS sensor data, etc.

13.3 Lessons Learned

Over the last 20 years there have been at least 9 dead bus events not counting multiple failures of identical spacecraft. Four of the satellites were restored to full operational capability and 5 were permanently lost. Several dead bus cases have publically available information including Galaxy 15, SOHO and ORBCOM. Historically, the most common causes for dead bus events have been traced to unexpected processor behavior, circuit design flaws, single point failures, and ground commanding errors.

Within the last few years four spacecraft have experienced dead bus events where two spacecraft were successfully recovered and two were lost. Only one of the recovered spacecraft was designed to recover and it performed exactly as designed with no mission degradation. All four spacecraft used Ni-H_2 batteries. Li-Ion batteries are now replacing Ni-H_2 and the most common type can be damaged or destroyed by excessive over-discharge. If the four spacecraft had flown batteries susceptible to excessive over-discharge damage all four spacecraft would have been lost. This illustrates the need for depleted battery prevention design and not reliance on software alone. More specific details are provided below.

Spacecraft A

- **Problem:** During transfer orbit a computer lockup resulted in loss of attitude control followed by battery depletion and bus collapse (affected both computers)
- **Root Cause:** Suspected part failure caused a computer lockup
- **Lesson Learned:** The solar array regulators were powered from the bus and could not restore power to the bus when the solar panels were in the sun and the mission was lost

Spacecraft B

- **Problem:** A massive bus short rapidly depleted the batteries with total loss of mission
- **Root Cause:** Known single point failure on primary bus; however, since all prior missions had no failures, no corrective action was taken
- **Lesson Learned:** Incorporate double insulation for all unfused power sufficient to reduce the probability of a bus short to non-credibility

Spacecraft C

- **Problem:** A loss of attitude control resulted in battery depletion and loss of bus voltage
- **Root Cause:** Unknown
- **Lesson Learned:** Bus voltage was successfully restored after several weeks of commanding despite exposure to extreme cold, with frozen batteries and propellant lines. The spacecraft was subsequently restored to full mission operability with no loss of capability

Spacecraft D

- **Problem:** Loss of attitude control followed by battery depletion and bus collapse
- **Root Cause:** Design issue caused an unforeseen locked out ground command capability
- **Lesson Learned:** The spacecraft was designed for dead bus recovery capability and the mission was immediately restored when the solar panels were in the sun

14. Design and Workmanship Verification

All flight hardware designs are required to successfully pass both qualification and acceptance tests (or proto-qualification when allowed by program) to validate its design and functionality. These test requirements are defined in SMC-016 for both mechanical and electrical units. For a new design development tests are often performed on representative articles to gather engineering data that characterizes the unit's performance to minimize design risk. Qualification testing provides a demonstration that the design, manufacturing, and acceptance testing produces flight items that meet specification requirements. Acceptance testing at the unit, subsystem, and spacecraft level demonstrates that flight hardware meets performance requirements and is free of workmanship defects. Programs with limited production runs may elect to perform a proto-qualification test with reduced margins on the flight unit in lieu of a separate qualification and acceptance test process.

As part of the design verification process, consideration needs to be given to mission operability. Test-like-you-fly (TLYF) philosophy focuses on determining the "mission-related" or "like you fly" risks associated with potential flaws in the space systems. Being able to demonstrate that a mission can be flown successfully is different than demonstrating a unit or subsystem meets requirement. As defined in TOR-2010(8591)-6 "The basic principles of TLYF":

1. The system should never experience expected operations, environments, stresses, or their combinations for the first time in flight
2. Do only smart things with the space system (don't knowingly expose flight hardware to damaging test conditions)
3. TLYF is a complement to other forms of test, not a replacement
4. When you can't test like you fly, do risk management

The following sections will discuss the standard approach to validating the design and workmanship of flight hardware as defined in common military and SMC standards for the Li-Ion battery and various electronic units at both a unit and spacecraft level. It will also discuss unique features of the hardware designs that need to be validated either as part of a qualification test program or as a separate test under the TLYF philosophy.

14.1 Li-Ion Battery

14.1.1 Developmental Tests

Developmental tests are commonly performed for a new cell technology or design or battery design. These tests typically consist of electrical, thermal, mechanical, and life tests performed at the cell, virtual cell, or battery level and cover a wide range of operating conditions. These tests support the TLYF approach and are defined in SMC-S-017.

14.1.2 Cell Level Tests

Cell level qualification tests can be performed on an initial cell lot typically used for building an integration and test battery. A flight lot of cells generally go through cell level acceptance or proto-qualification test for the purpose of cell buy-off and/or cell selection. At this time no specific standard is written that define these tests, but testing will typically encompass battery level electrical performance tests defined in SMC-S-017 at a minimum.

A quantitative helium leak check prior to cell activation is recommended on 100% of the cell lot as it has been demonstrated that electrolyte can “plug” very small leakage paths and cells that would fail a pre-activation helium leak test will pass once electrolyte has been introduced.

It is recommended that cell level X-rays be performed on 100% of flight hardware. X-ray inspection has proven effective for cell workmanship verification, specifically in regard to electrode leads, foreign objects and debris (FOD), weld integrity, and stack and internal component alignment. From a safety perspective, particulate contaminants inside a cell can move during vibration, and need to be carefully controlled to prevent internal cells shorts that can lead to thermal runaway. Cell level X-rays are standard mission assurance requirements for prior Ni-Cd and Ni-H2 space batteries.

14.1.3 Virtual Cell/Module Level Tests

A program may elect to perform qualification (or proto-qualification) and acceptance testing at the virtual cell/module level for either flight selection and/or risk reduction prior to building the full flight battery. At this time no specific standard is written that define these tests, but testing will typically encompass battery level electrical and mechanical performance tests defined in SMC-S-017 as a minimum.

14.1.4 Flight Battery Level Tests

Qualification and acceptance test requirements for flight Li-Ion battery are defined in SMC-S-017. Several areas of clarification are provided.

> **Leak Test:** It is not uncommon for cell leak tests to be performed throughout the cell and battery build process. These tests can vary from a qualitative to quantitative test to aid in cell selection and risk reduction for battery level tests. However, the intent of SMC-S-017 is that a quantitative leak test be performed at the battery level pre- and post- environment tests.
>
> **Pressure Test:** The AIAA-S-080 document defines the required tests for both pressure vessels and sealed cells. At minimum for qualification cell-level proof pressure testing and burst tests are required as defined in SMC-S-017 for both pressurized and sealed cell designs. At minimum for acceptance test flight cell testing requires 100% proof pressure test as defined in SMC-S-017 for both pressurized and sealed cell designs.

14.1.5 Low Temperature Survival Verification Tests

As part of a test as you TLYF philosophy the following tests are recommended to verify that the type of battery cell used in the power system can tolerate the conditions typically encountered during a dead bus event. These tests include: low temperatures, full discharge, parasitic loads, and cold recharge. Since different cell designs respond differently to a dead bus environment, these tests should be performed for all cell designs that may be used in the power system. The tests may be performed individually, or they may be combined into a single worst case test on a full-sized battery that puts the battery through simulated dead bus and recovery environments, and finally re-verifies battery performance.

> **Low temperature exposure test:** During a dead bus event, the discharged and open circuited battery could be exposed to very low temperatures. A test is recommended to verify that the fully discharged battery cell can survive non-operating temperatures down to as low as -70°C, or alternatively to a low temperature prediction based on the worst case thermal model of possible dead bus conditions.

Low temperature parasitic load test: After a battery is disconnected from the system loads, there are often parasitic loads that still drain the battery and individual cells at low rates. The worst case parasitic loads should be based on analysis of the circuits that remain connected to the battery during the dead bus event. A test is recommended to verify that the fully discharged battery cell can survive the worst case parasitic load discharge for up to two weeks at temperatures as low as -70°C, or alternatively to a low temperature based on the worst case thermal model of possible dead bus conditions.

Low temperature recharge test: Upon recovery of power, the cold battery will be subject to recharge at a peak current and to a peak voltage level that are determined by the power system default settings. A test is recommended to demonstrate that the battery will not be irreversibly damaged by the peak current in combination with the peak voltage setting. Such a test should realistically include:

a) stabilization of the fully discharged battery at -50°C, or the worst-case expected battery temperature extremes

b) application of the charge current and voltage limit along with the default battery heaters and charge control current and voltage settings at the initiation of recovery

c) verification that no individual cells are driven over 4.2 volts for more than 30 seconds during recharge

d) verification that battery capacity and discharge power shows less than 5% performance degradation when returned to normal operating conditions

This test must be done on a battery containing the full complement of series-connected cells, since verification that all individual cells remain below 4.2 volts during recharge is a key requirement during this test that will be affected by the number of cells in series.

14.1.6 Life Tests

Each satellite program needs to satisfy life qualification requirements as defined in Section 4 of SMC-S-017. The life test cells need to be produced from the same drawings, using the same materials, tooling manufacturing process, and level of personnel competency as used for flight hardware. Life test articles should be manufactured with the greatest range of raw material lots and electrode and manufacturing batches as pragmatically possible to understand lot-to-lot variability. Life test articles should be subjected to at least acceptance test level vibration environments prior to life testing. It's recommended that real time testing be at the battery level to quantify thermal divergence among cells and the extent of degradation in capacity and resistance, as well as qualify the real time performance of any cell balance electronic hardware. Emphasis should be on creating a thermal control system that will simulate flight like temperature, including expected exotherm during discharges. Life testing should start as early as possible, encompass worst case mission operation and continue for full mission duration to reduce program risk per the guidelines in TR-2006(1455)-1. Voltage, resistance, and capacity EOL measurements from the real time life test provide the basis for establishing EOL electrical and thermal thresholds. Other accelerated type life tests may be performed at the cell, virtual cell or battery level to facilitate Li-Ion life model development when real time life test is less than 100% complete.

Additional flight lot life tests provide a method to reduce program risk in situations where lot-to-lot variability exists. One such example is where key raw materials are stockpiled for extended duration.

Testing could be at the cell or virtual cell level. It is recommended that life testing start as early as possible after procurement of flight cells and continues for full mission duration to reduce program risk. This approach typically relies on accelerated testing that is compared to previously performed real time life test and similar accelerated test on baseline cells.

14.2 Cell Balance Electronics (CBE)

The need for, and operational characteristics of, CBE are discussed in detail in Section 9 of this document. This section addresses testing considerations unique to the CBE. For the CBE, there are unique considerations depending on how the CBE is packaged (integral with the battery assembly or as a separate assembly), and depending on whether or not the CBE is operational during a dead-bus fault recovery.

14.2.1 Packaging

If the CBE is packaged in an assembly that can be tested separately from the battery cells, then it should be tested to the same standards and criteria applied to other electronic elements on the spacecraft (note – a possible exception may apply, as described in the next section). Typically this entails an environmental test sequence (vibe, shock, thermal vac, etc.) that interleaves comprehensive functional and performance testing of all operating modes, including key fault modes as required by the program. Special test equipment incorporating a battery or cell simulator is recommended for functional and performance testing the CBE. Use of a battery or cell simulator assures that each of the balance circuits in the CBE (typically 8 circuits for a 28V battery system) can be individually exercised during the test program. It also provides flexibility for simulating fault and/or non-balanced conditions that may not be as readily simulated if the CBE were connected to actual Li-Ion cells.

If the CBE is packaged in an assembly that is common with the battery cells, there are additional challenges that must be addressed in order to implement an effective test program. One challenge is that the preferred test temperature ranges for electronic elements such as the CBE are in excess of the allowed temperature range for typical Li-Ion cells. Testing the battery over the CBE preferred test temperature range would result in over-testing the Li-Ion cells. Another challenge is in regards to assuring that all of the CBE circuits are functionally exercised. For example, with a shunt topology CBE (see Section 10), it is common for there to be one or more cells in a battery whose intrinsic performance results in no current shunting at the end of the battery recharge cycle. In order for the CBE design to be effectively qualified, or for the CBE flight hardware to be effectively accepted for flight usage, the circuits may need to be tested as a sub-assembly separate from the battery cells.

14.2.2 In-flight Operations

There may be special test considerations applicable to the CBE depending on the system design approach taken for meeting Depleted Battery Recovery requirements. As discussed in Section 11 “Depleted Battery Recovery and Maintenance,” shedding certain spacecraft loads is a typical response to an anomalous low-voltage/low-SOC condition. If the CBE is one of the elements planned to be turned off – and ultimately re-started as part of the Depleted Battery Recovery process – there may be interface conditions (low input voltage and/or low baseplate temperature) at CBE turn-off/ turn-on that are unique from other spacecraft electrical components. Consistent with the TLYF philosophy, these unique conditions must be accounted for in the CBE qualification and/or acceptance test programs.

14.3 Cell Bypass Unit (CBU)

The need for, and operational characteristics of, the Cell Bypass Unit (CBU) are discussed in detail in Section 11 of this document. This section addresses testing considerations unique to the CBU. For the CBU, there are unique considerations depending on the functional characteristics of the CBU (autonomous vs. commandable, resettable vs. non-resettable). Note that the following sections assume the CBU is integral to the battery assembly, and that the CBU is of the type described in Section 11.4.2 (cell bypass with cell disconnect).

14.3.1 Resettable CBU

In theory, resettable CBU can be acceptance tested on actual flight hardware at the battery assembly level. However, due to the risks associated with bypassing an otherwise healthy cell, it is advisable that the functionality be tested at the CBU sub-assembly level (using a battery or cell simulator) rather than on a flight battery. This approach also allows the CBU to be tested over environmental ranges more typical of other electronic components on the spacecraft, rather than the more limited range typical of a battery assembly.

14.3.2 Non-resettable CBU

If the CBU is not resettable, then the actual flight CBU cannot be functionally tested. For non-resettable CBUs, means to passively verify the integrity of the flight unit are necessary, and the functional/performance capabilities of the CBU would necessarily only be possible on a qualification device. Another method employed to reduce the risks associated with non-resettable CBUs (similar to what is done for other “one-and-done” devices, such as fuses and NSIs) is to conduct Lot Acceptance Testing. These tests statistically validate the acceptability of a device for flight, based on the performance of other devices from the same production lot.

14.3.3 Commandable vs. Autonomous CBU

As discussed in Section 11, a commandable or autonomous CBU may be used in a Li-Ion battery design. It is advisable to perform functional testing of the CBU using a simulated cell rather than an actual cell. Use of a simulator allows a high-impedance failure signature to be introduced in a controlled manner.

14.4 Battery Disconnect and Maintenance System (BDMS)

The need for, and operational characteristics of, the Battery Disconnect and Maintenance System (BDMS) are discussed in detail in Section 12 of this document. This section addresses testing considerations unique to the BDMS.

By its nature, the BDMS must perform its critical functions under more extreme conditions than other electrical components on the spacecraft. Since battery disconnect occurs when the battery SOC and voltage have reached critically low thresholds, the BDMS must operate effectively with its primary input power at a much lower voltage than other spacecraft hardware. Also, most if not all spacecraft heaters will be disabled during a Dead Bus event; therefore, it is likely that the BDMS must be capable of operation at much lower temperatures than typical spacecraft components. The component qualification and acceptance test programs must account for these unique aspects of BDMS operation.

It should be noted that strict adherence to the TLYF philosophy is likely not possible when it comes to testing the performance of the BDMS at the system level. Although the functionality of the BDMS may be testable during system-level testing (see Section 12.4.1), performance under flight-like thermal conditions (i.e., extremely cold temperatures) is likely not justifiable due to the stress that would be imposed on other system components. An argument can be made that strict adherence to TLYF is not required in this case, since entry into a Dead Bus condition and subsequent Dead Bus Recovery are not intended operational modes, but instead are “last-ditch” responses to a major fault event.

14.5 Electrical Power Subsystem Test Bed Tests

For verification of certain performance requirements that potentially place flight hardware at risk, and/or for development of new system designs, an Electrical Power Subsystem (EPS) Test Bed can be implemented. The test bed will typically consist of the elements discussed above (Battery, CBE, CBU, BDMS) and other relevant EPS components (charge/discharge controller, converters, peak power trackers, etc.). Power sources such as solar arrays are typically simulated, as are most spacecraft loads.

The test bed environment gives the power engineer an opportunity for testing that cannot be reasonably achieved during either the component or system level testing, including detailed investigations of EMI/EMC, transient behaviors, loss characterizations, and system stability. Since there are typically inherent risks associated with deep depletion of Li-Ion cells, an EPS test bed incorporating a non-flight battery is an excellent environment in which to verify the overall system capability to execute dead-bus entry, maintenance, and recovery.

14.6 Spacecraft Level Verification

The basic purpose of EPDS testing at the vehicle level is to ensure reliable delivery of power to the bus and payload equipment. This testing can be divided into two parts – configuration validation and performance validation.

Configuration validation is accomplished through polarity checks, proper connector matings, and wiring integrity. Performance validation consists of power quality assessments, verifying commandability of EPDS components, verifying redundancies, verifying expected operation with solar arrays (usually done with Solar Array Simulators (SAS)), assessing step load responses, verifying fault management response, and validating charge management functions.

For Lithium Ion systems, many of these test operations remain the same as for Nickel Hydrogen or other battery types. It is primarily in the verification of fault management functions and charge management functions that Li-Ion systems will be different.

14.6.1 Special Test Equipment (STE) Implications for Li-Ion Systems

As Li-Ion batteries are more sensitive to overcharge and over-discharge than other type, and given the safety issues associated with Li-Ion, it is important that the STE for these systems is designed with sufficient safeguards to prevent either overcharge or over-discharge. This would include such items as:

- Voltage and current limiting of ground power sources
- Battery voltage and current monitoring, as well as temperature monitoring, with automatic removal of ground power sources (including shutdown of SAS), or disconnect of vehicle battery, if either go out of safe operating area

  - These protect not only against STE faults, but faults in the EPDS hardware or charge-management software
- Test procedures that call for positive confirmation of any changes to STE current-limit settings (avoid inadvertent mis-setting by STE operators)
- Failure Modes and Effects Analysis (FMEA) to understand how failures of circuit components in STE may cause uncontrolled charging of batteries
- Use of a second means of battery disconnect in case of failure in primary STE
- Auto-detection of dangerous battery conditions and automatic alarm issuance to alert personnel to the condition

14.6.2 Use of Battery Emulators

A battery emulator (or simulator, as it is sometimes called), is an electronic unit whose terminal I/V characteristics mimic those of a real battery, including realistic charge and discharge SOC excursions with time. A battery emulator for a Lithium Ion battery might also be designed to have equivalent cell voltage connections so that cell-balancing electronics could be tested.

Use of a battery simulator for vehicle test eliminates safety concerns that would be encountered with an actual battery. But some vehicle testing should be conducted using an actual Li-Ion battery. This would be a test battery (or batteries, as the case may be) for most large, high-reliability vehicle, with flight batteries not installed until after thermal vacuum vehicle test. For smaller spacecraft, Class C or D missions, flight batteries are often integrated earlier, going through thermal vacuum testing along with the spacecraft. Whenever an actual battery, whether a test battery or a flight battery, is installed on the vehicle, contingency plans and emergency response equipment (fire extinguishers, respirators, etc.) should be in place to respond in case of overtemperature conditions, up to and including fire or explosion.

14.6.3 Cell-Balancing Electronics

An issue unique to Li-Ion is the use of cell-balancing electronics. Whether or not this function needs to be tested at the vehicle level is subject to debate. If a battery emulator is employed that has been designed for the purpose, then testing of the cell balancing function can be easily accomplished. In fact, the emulated cells or “pseudo-cells” could just be large capacitors for testing purposes. Initial values of voltage could be switched onto individual capacitors, and then the balancing electronics could be operated to prove that within some reasonable period of time, these pseudo-cell voltages are equalized.

This method is preferable to testing with an actual battery for two reasons. First, using a real battery would require that imbalances be deliberately introduced, which is something that carries some small risks of battery harm and/or safety concerns, depending on how it is done. Second, the time it would take to restore cell balance would be greater than with the pseudo-cell approach.

14.6.4 Battery Installation Using DBP disconnect Switch

If a battery disconnect switch (or switches, for multiple battery systems) has been designed in as part of a Depleted-Battery Prevention (DBP) scheme, this switch can be used to aid in safe installation or removal of spacecraft Lithium Ion batteries. If the switching controls have been designed such that the disconnect relay will not open or close unless the voltage on either side of the contacts has been equalized (see Sections 12.1.4 and 13.2.1), then this function may be safely employed to open or close the relay during ground test of the spacecraft. A separate input to the switching circuit could be designed in expressly for this ground test purpose (however, redundancy or interlocks should be employed to eliminate the chance of an inadvertent connect or disconnect on the ground or in flight).

14.6.5 Telemetry and/or Instrumentation

When flight batteries are used at any time during vehicle testing, telemetry or ground instrumentation should be used to measure overall battery voltage, temperature and, if possible, cell voltages to the greatest accuracy readily achievable. This data should be stored and used for trending purposes. Whereas Nickel Hydrogen batteries are forgiving of occasional overcharge or undercharge, Lithium Ion batteries are less forgiving, so it is important to be able to see the total time history of flight batteries so that signs of degradation can be detected.

15. Class A, B, C, and D Missions

Li-Ion batteries are becoming more frequently used in all classes of space missions. Mission classes A, B, C, and D are defined and discussed in MIL-HDBK-343 and NASA NPR 8705.4. There is also a previous MAIW paper from 2011, "Mission Assurance Guidelines for A-D Mission Risk Classes," which provides a very thorough treatment of all aspects of program execution, oversight, risk management, and lessons learned for the four risk classes. That document contains a useful table describing the characteristics of the four risk classes, which is reprinted here for convenience.

Table 15-1. Class A, B, C, and D Mission Characteristics
(Note: Actual document should be referenced due to potential updates)

Characteristic	Class A	Class B	Class C	Class D
Risk Acceptance	Minimum Practical	Low Risk	Moderate Risk	Higher Risk
National Sig	Extremely Critical	Critical	Less Critical	Not Critical
Payload type	Operational	Operational or Demo Op	Exploratory or Experimental	Experimental
Acquisition costs	Highest	High, LCC	Medium LCC	Lowest, LCC
Complexity	Very high – High	High – Medium	Medium – Low	Low – Medium
Mission Life	>7 years	≤7 years	≤4 years	< 1 yrs
Cost	High	High to Medium	Medium - Low	Low
Launch Constraints	Critical	Medium	Few	Few – None
Alternatives	None	Few	Some	Significant
Mission Success	All practical measures	Stringent/minor compromises	Reduce assurance stds	Minimal assurance stds
Typical Contract Type	CPAF*	CPAF-FFP	CP-FFP	FFP

From a general EPDS perspective, mission class translates into somewhat less stringent requirements for the qualification, design, and implementation of EPDS components for Class B, C, and D missions. Requirements for Class A missions are contained in AIAA S-122-2007, which was written to be the "Gold" standard for EPDS design. Key requirements include power margin as a function of design maturity, battery management, power quality, protection against insulation failure and plasma arcs, design and construction requirements, and verification (test and analysis) requirements. There is also a requirement for dead bus recovery, but it contains an exception for Li-Ion batteries. This exception was inserted based on the committee's feeling at the time that a disconnect switch would be too difficult and costly to implement and might adversely affect overall reliability. However, general industry sentiment today is that a disconnect switch should be implemented, at least on Classes A and B missions. There have been several incidents of dead buses or depleted batteries in the past several years, which have served to remind the community that a dead bus is a realistic threat, even though it is often difficult or impossible to foresee which insidious faults or combination of circumstances can lead to a dead bus situation.

EPDS is a critical subsystem for any spacecraft, regardless of mission class, since all payloads and bus units need power in order to operate. Therefore, it is important to follow the best practices for producing robust Power Management and Distribution (PMAD) hardware, solar panels and arrays, and batteries.

For PMAD in general, there is little excuse for not designing equipment, regardless of mission class, to be robust in the areas of power quality, double insulation of unfused power, separation of primary and redundant functions (to minimize possibility of failure propagation), prohibition of bare metal (to preclude plasma arcing), proper fusing or current-limiting techniques, etc.

For solar arrays and panels, established materials should be used and best construction practices should always be followed, regardless of mission class. For lower classes of missions, testing of coupons or panels may not be as stringent as for Class A missions, but some testing must generally be done for new designs, depending on mission duration and orbital environment.

For batteries, the shorter mission durations for some Classes C and D missions takes away some of the burden of battery qualification and may similarly obviate the need for cell balancing or bypass. The issue of whether to include DBP for lower-class missions is discussed below.

Qualification of Li-Ion batteries for long-duration Class A missions has historically been very difficult to accomplish and it still is, to some extent, a moving target. This is because even a minor change in cell chemistry or substitution of materials can render life test data largely obsolete. Since life testing must be done in real time or with only limited acceleration, a change to the battery under test might require beginning a new, also real time, test. Efforts to stockpile materials have been made by the government to ensure consistent battery production in the future, so that life testing results will remain valid in the long term.

Some of the degradation mechanisms in Li-Ion batteries are related to calendar time, as opposed to operational time. The shorter the mission duration, the less of a factor calendar time plays in the reliability of the battery. This means that batteries for Class C and D missions are unlikely to require elaborate life tests – suitable batteries may be selected off the shelf. If used at a reasonably conservative DOD and within a reasonable temperature range, there is a high chance that they will last for the required mission length.

Ideally, all spacecraft using Li-Ion batteries should have a means of preventing over-discharge. Indeed, design of new equipment should include a disconnect switch and protocols for disconnect and reconnect should be built into the hardware and software of the system. The European Space Agency has made such switches standard equipment, and the Japanese agency JAXA has been leaning in the same direction. However, there are many USG Class C and D missions that use legacy hardware for their PMAD, and this equipment has not traditionally included disconnect switches.

The risk of a depleted battery for Class C and D missions is greater than that for Class A or B for the following reasons:

- Lack of, or less robust Fault Management functionality
- Less thorough verification and validation of mission software, including battery management functions
- Lack of hardware redundancy

- Less codified ground operational procedures, increasing probability of commanding errors or other misjudgments
- Lower launch vehicle reliability, increasing chances of attitude problems after separation
- Lower grades of Parts (including COTS) and Materials, and less robust processes
- Greater risk in wiring harnesses and other PMAD elements
- Parasitic power loads due to failures in payload equipment or instruments

Despite these factors, it is possible to minimize the risk of a depleted battery by following these guidelines:

- Minimize risk of bus faults through low-cost robust practices in PMAD construction
  - Double-insulate unfused power
  - Eliminate bare metal on voltages higher than 15V
  - Ensure no pure tin platings on any components
  - Use adequate layer separations in Printed Wiring Board designs (especially where unfused power is routed)
  - Separate primary and redundant functions where possible
    - Separate connectors
    - No overlap in printed wiring boards
- Conduct "Do No Harm" analysis for every user load
  - Ensure proper fuse or electronic circuit breaker sizing
  - Look for failure modes that could produce fault current up to twice the main fuse rating
- Ensure that PMAD can be powered directly from solar arrays
  - Powering from bus only implies that once battery is dead it cannot be recharged
- For systems that switch solar array segments to the bus, provide enough "hardwired" segments to provide some charging capability to the batteries in a low-voltage scenario
- Place solar panels with respect to spacecraft natural spin axis such that they are more likely to remain sun pointing
- Provide a robust Safe Mode that places the vehicle in a sun-safe attitude in case of problems
  - Using a different processor than the main spacecraft processor helps in cases where the main processor has malfunctioned or upset
  - Provide load shedding ability
    - Prolongs the time until the battery becomes depleted
    - Turn off all heaters
    - Turn off even essential equipment (including PMAD) if battery reaches undervoltage limit
- Only if independent recharge capability is built in
- May be able to reduce battery load to very small level, even without a disconnect switch

  - Some low discharge rate may actually prevent or delay battery freezing
- Requires ability to restart PMAD autonomously
- Use cell designs more tolerant to low voltage discharge

16. Safety

16.1 General

This section presents safety considerations, guidelines, and best practices associated with the development, testing, storage, handling, transportation, and operation of secondary (i.e., rechargeable) Li-Ion battery assemblies as part of spacecraft Li-Ion based power subsystems. This section is included to: 1) aid in understanding compliance with applicable safety requirements, primarily Range Safety requirements and Department of Transportation (DOT) requirements, that directly affect the design and testing of battery cells, batteries, the power subsystem, and electrical ground support equipment, and 2) provide the framework for the project system safety engineer to prepare the necessary safety analysis and safety documentation supporting requirements compliance.

Safety is addressed at the cell-level, battery-level, and spacecraft power subsystem-level. Charging/discharging ground support equipment is addressed to the extent it interfaces with the battery assembly during assembly, integration, and test activities as well as spacecraft launch site processing operations. Safety data requirements, including required safety analyses are addressed. Information from a variety of sources relating to Li-Ion batteries and their aerospace applications has been collected and included herein. The sources used are listed in the reference section.

16.1.1 Application

This safety section discusses various safety requirements and best practices related to the development of spacecraft power subsystems utilizing Li-Ion battery technologies. It is intended to provide project managers and systems engineers information pertinent to battery safety including an understanding of various design safety features and operational controls. It may aid battery and power subsystem design engineers in the selection of various design safety features that can be credited to ensure the safety of personnel, flight hardware, facilities, and equipment. Assembly, integration and test personnel may find this section useful to understanding safety aspects related to handling and transportation and launch site processing. The project system safety engineer can utilize this section to better understand the launch site safety certification processes.

The safety information provided herein does not provide any design or operational direction, either formally or informally, to contractors, subcontractors, vendors, battery manufacturers, or regulatory agencies. Use of this information does not assure compliance with safety requirements. Additionally, this information is not intended to recommend one Li-Ion based power subsystem architecture or Li-Ion battery design and/or application over another from a safety standpoint. Each design should be considered unique and evaluated for safety on a case-by-case basis.

16.1.2 System Safety Process

A system safety process flow is presented below in Figure 16-1. Because compliance with applicable safety requirements significantly influences design, it is important that the system safety effort begin early in the project life cycle. Failure to identify necessary design safety features, including those related to successful testing, and incorporate them into the design process early in the project life cycle can result in later non-compliances and costly design changes.

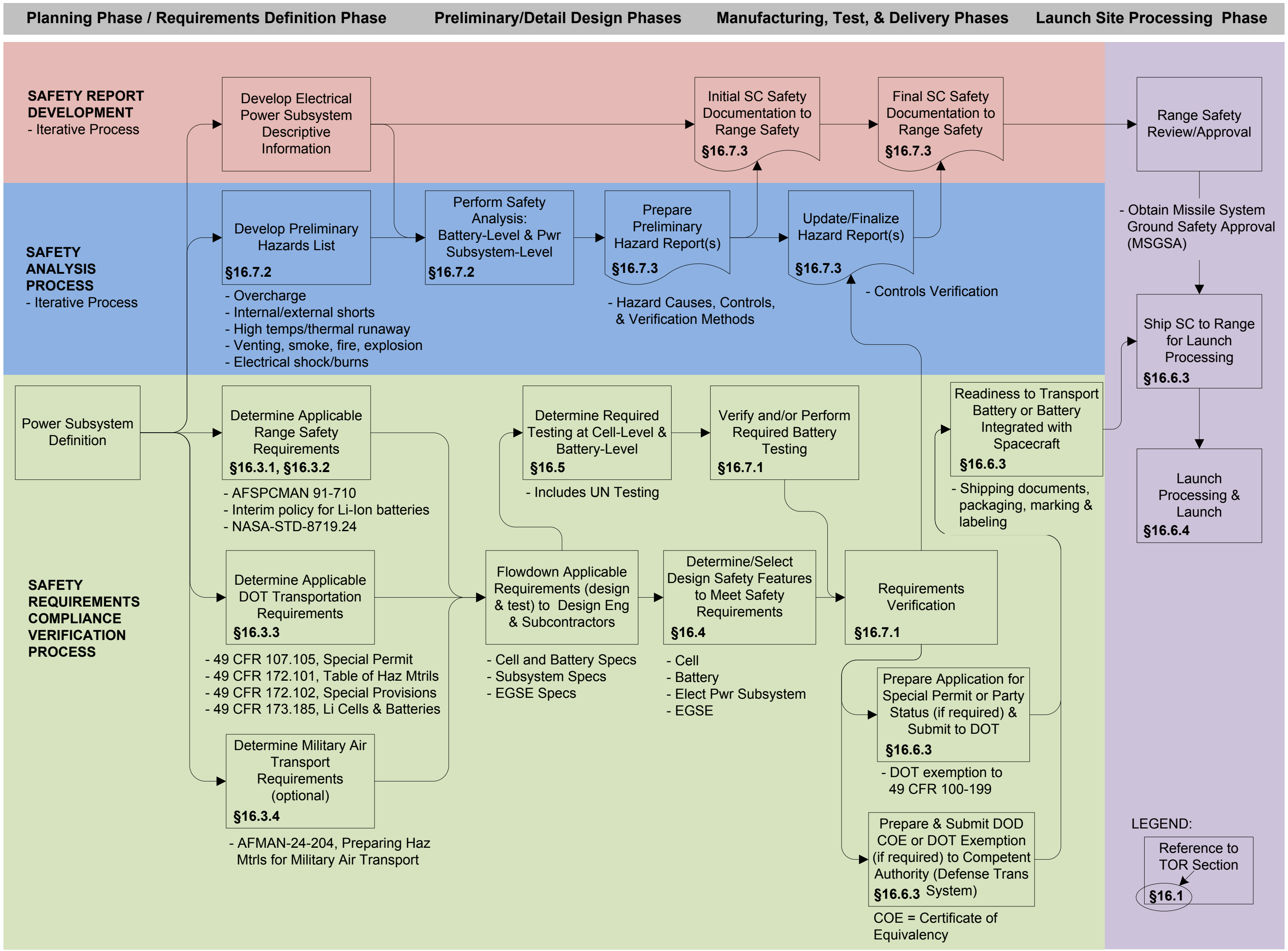


Figure 16-1. Li-Ion battery safety process flow.

16.2 Li-Ion Battery Risks

Failures of Li-Ion cells and batteries can occur due to poor cell design, cell manufacturing flaws, external abuse of cells (thermal, mechanical, or electrical), poor battery assembly design or manufacture, poor battery electronics design or manufacture, or poor electrical ground support equipment (i.e., battery charging/discharging equipment) design or manufacture.

The primary Li-Ion battery risks are a result of:

- overcharge
- external and internal shorts
- high temperatures
- over-discharge

Each of these conditions can result in thermal runaway, release or venting of toxic and/or flammable materials (i.e., electrolyte and/or gases), fire and explosion.

Thermal runaway is a condition that occurs when a cell begins generating heat in a self-sustaining or even self-accelerating manner. At elevated self-heating temperatures possible cell explosion can occur. Thermal runaway is sensitive to the cell SOC, higher SOCs correlate with lower onset temperatures. Venting of toxic materials is a hazard to processing personnel while venting of flammable gases in the presence of oxygen and an ignition source can result in fire and explosion, damage to equipment, and/or injury to personnel. In some cases overcharge conditions can lead to the deposition of lithium metal that can create internal shorts in the cell.

The electrolyte in Li-Ion cells contains flammable organic solvents and under high voltage conditions, can decompose leading to the formation of gases (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.

An external short of a Li-Ion cell can result in very high current spikes that cause high pressures inside the cell resulting in cell venting or explosion. Li-Ion cells when deformed due to physical damage (causing internal shorts) can also go into thermal runaway. Slight deformation of the cell can result in electrolyte leakage and a smaller rise in temperature while larger deformations (fast and heaving crushing) can result in cell venting, smoking and fire.

Li-Ion battery safety must be assessed at the system-level that includes the component cells, battery, battery assembly (multiple batteries), battery electronics, the spacecraft power subsystem, and electrical ground support equipment used for battery charging and discharging. Only with a systems approach can safety be assessed for all known failure modes.

16.3 Safety Requirements/Guidelines

Safety requirements and guidelines discussed in the following sections should be flowed down in product specifications for battery cells, battery assemblies, power subsystems, and electrical ground support equipment as appropriate. It is important that applicable requirements be identified and allocated to design engineers and operations personnel early in the product development life cycle (during requirements review and preliminary design phases) to ensure a safe and compliant design.

16.3.1 Air Force Space Command Range Safety Requirements

Air Force Space Command Manual (AFSPCMAN) 91-710, Range Safety User Requirements, establishes the system safety program requirements, minimum design, test, inspection, hazard analyses, and data requirements for hazardous and safety critical launch vehicles, payloads, and ground support equipment, systems, and materials for Air Force Space Command (AFSPC) ranges, including the Eastern Range (ER) and Western Range (WR). Volume 3, *Launch Vehicles, Payloads, and Ground Support Systems Requirements*, Chapter 14, *Electrical and Electronic Equipment*, addresses general design, electrical ground support equipment battery charging equipment, and flight hardware battery requirements. AFSPCMAN 91-710, Volume 6, *Ground and Launch Personnel, Equipment, Systems, and Material Operations Safety Requirements*, addresses battery operations while at the Range. Additionally, the Air Force issued Interim Policy Regarding EWR 127-1 Requirements for System Safety for Flight and Aerospace Ground Equipment Li-Ion Batteries, which supplement the requirements of AFSPCMAN 91-710. Key Range Safety requirements are summarized below.

General Design Policy:

General design policy requires that if a system failure may lead to a catastrophic hazard, the system shall have three inhibits (dual fault/failure tolerant); if a system failure may lead to a critical hazard, the system shall have two inhibits (single fault/failure tolerant); and if a system failure may lead to a marginal hazard, the system shall have a single inhibit (no fault/failure tolerant). Since overcharging during launch processing at the Range can lead to battery or cell explosion or fire resulting in loss of spacecraft, or worse if propellants have been loaded (i.e., loss of payload processing facility, launch vehicle, or launch support facility) and/or injury or death to personnel it is considered a catastrophic hazard. Required inhibits shall be electrical and/or mechanical hardware and shall be independent and verifiable. These inhibits can be part of the system design, which includes battery cells, battery electronics, the power subsystem, and battery charging/discharging electrical ground support equipment.

Flight Hardware Battery Design Requirements:

General design requirements address:

- battery case factors of safety and pressure relief capabilities
- high pressure protection for individual cells
- minimizing the use of toxic, reactive, flammable and combustible materials
- battery connectors that prevent reverse polarity
- prevention of reverse current causing a hazardous condition,
- positive protection against shorting battery terminals or connector plugs when the battery is not connected to the system
- proper battery identification

Because batteries and cells may be classified as special pressurized equipment, additional pressure system design, analysis and test requirements may apply including:

- minimum burst factor of safety

- demonstration of leak-before-burst failure mode
- fatigue-life analysis
- random vibration testing
- thermal vacuum testing
- pressure cycle testing
- proof pressure testing
- non-destructive inspection

Electrical Ground Support Equipment Battery Charging/Discharging Requirements: Electrical ground support equipment requirements include:

- accessibility for electrical disconnection and/or battery removal
- battery connectors that prevent reverse polarity
- current limited equipment designs
- prevention of charging above 4.4 volts and discharging to less than 0 volts
- individual cell monitoring and recording
- temperature monitoring
- use of dedicated and intrinsically safe (if required) equipment
- certification of equipment prior to first operational use on the Range

Li-Ion Battery Test Requirements

Test requirements include:

- cell pressure relief device testing
- constant current discharge and reversal testing
- short circuit testing
- drop testing

Handling, Transportation, and Storage Requirements:

Transportation requirements include compliance with Department of Transportation (DOT) requirements for shipment of hazardous materials including proper labeling. Li-Ion batteries that are transported while incorporated into flight hardware (i.e., integrated with spacecraft) must be approved by Range Safety on a case-by-case basis. Li-Ion batteries not incorporated into flight hardware and transported on publicly accessed roadways shall not exceed 50% of rated charge. If lithium content exceeds 8.0 grams per battery, transportation packaging of individual batteries shall have caution labels in accordance with CFR 173.185. Approved temporary storage and handling facilities for Li-Ion batteries and off-site disposal while at the Range is also addressed. DOT requirements are discussed in more detail in Section 16.3.3.

Operations Requirements:

Operations requirement include:

- battery operations training and certification
- emergency first aid and personnel protective equipment
- procedures
- battery maintenance and storage

Flight Hardware Battery Design Data Requirements:

A detailed description of flight hardware battery design data and information is required to be submitted to Range Safety as part of a safety data package through which missile system pre-launch safety approval is obtained. Required information includes:

- operator parameters of the battery
- cell chemistry and physical construction
- cell vent parameters, toxic chemical emission, and evaluation of hazards
- EPA/DOT classification of the battery
- description of safety devices, case design, and vent operations
- description of operations including packing, transportation, and storage configuration, activation, installation, checkout, charging, usage, removal, and disposal
- identification of hazards with each activity
- qualification and acceptance testing results
- battery size and weight
- description of related EGSE
- list and summary of test plans, procedures and result.

It is important to note that the range safety requirements state that these requirements “are not applicable to Li-Ion batteries used in Underwriters Laboratories (UL) or MSA-approved appliances that have Li-Ion batteries as part of the certification.” To date no spacecraft battery assemblies have been UL listed. Therefore, the above exemption cannot be taken and all of the above requirements applicable at the battery-level must be met in order to process a spacecraft containing Li-Ion batteries at the Eastern or Western Ranges.

16.3.2 NASA Safety Requirements/Guidelines

NASA safety requirements for Li-Ion batteries primarily reside in NASA-STD-8719.24, NASA Expendable Launch Vehicle (ELV) Payload Safety Requirements. This standard was published by NASA to provide technical safety requirements for unmanned orbital and unmanned deep space payloads that fly onboard ELVs. The requirements in the standard were developed jointly by NASA and Air Force Range representatives (30th and 45th Space Wings). The standard is a mandatory NASA standard to be applied to NASA ELV payload project contracts or agreements as cited in NPR 8715.7, *Expendable Launch Vehicle Payload Safety Program*. For NASA programs, all Li-Ion battery designs must be reviewed and approved by both Range Safety and the NASA Payload Safety Working Group. The requirements of NASA-STD-8719.24 generally mirror those of AFSPCMAN 91-710 noted above and are not repeated here.

In addition to the NASA-STD-8719.24 requirements there is additional design guidance provided in several NASA publications including: *Battery Safety and Design Manual for Payloads* prepared by NASA Glenn Research Center and *Guidelines on Lithium-ion Battery Use in Space Applications* prepared by the NASA Engineering Safety Center Battery Working Group. These guidelines discuss standard approaches for defining, determining, and addressing safety for Li-Ion batteries to help the implementation of the technology in aerospace applications. NASA recommends that government and industry users and vendors of Li-Ion battery technology for space applications use these documents for appropriate safety guidance prior to implementing the technology.

16.3.3 Department of Transportation Requirements

Shipping of Lithium cells and batteries within the United States are addressed in the Code of Federal Regulations (CFR), Title 49, *Transportation,* Subtitle B, Chapter 1, *Pipeline and Hazardous Materials Safety Administration*. Key sections include those listed below. The requirements of each section are discussed in subsequent paragraphs.

- 49 CFR Part 107, Hazardous Materials Program Procedures
    - 49 CFR §107.105, Application for Special Permit
    - 49 CFR §107.107, Application for Party Status
- Part 172, Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, Training requirements, and Security Plans
    - 49 CFR §172.101, Table of Hazardous Materials and Special Provisions
    - 49 CFR §172.102, Special Provisions
- Part 173, Shippers-General Requirements for Shipment and Packaging
    - 49 CFR §173.24, General Requirements of Packagings and Packages
    - 49 CFR §173.185, Lithium Cells and Batteries

16.3.3.1 Table of Hazardous Materials and Special Provision

The Table of Hazardous Materials and Special Provisions includes three entries for the shipment of Li-Ion batteries. One is for shipping lithium batteries contained in equipment, which establishes the requirements for shipping batteries integrated with a spacecraft. The second is for shipping batteries packed with equipment, which covers shipping batteries with a spacecraft but packaged separately. And the third is for shipping batteries not contained in equipment or packed with equipment. The table identifies the hazard class or division, United Nations (UN) identification number, packaging group, label codes, special provisions, packaging requirements and quantity limitations. Special provisions, packaging requirements and quantity limitations are discussed further.

Special Provisions: Special provisions for Li-Ion batteries are in addition to standard requirements for packaging prescribed in §173.24.

SP 29 – excepts production runs of not more than 100 lithium cells or batteries from UN Manual of Tests and Criteria testing if the equivalent lithium content is not more than 1.5 grams per cell, the aggregate equivalent lithium content is not more than 8 grams per battery, and the batteries are packaged to meet Packaging Group I requirements. It is unlikely that this special provision can be taken for large space batteries therefore UN testing would be required.

SP 188 – excepts small lithium cells and batteries, including cells or batteries packed with or contained in equipment, from compliance with other requirements of Subchapter C, *Hazardous Materials Regulation*, provided the requirements of this provision are met. Requirements of this provision include:

- The equivalent lithium content is not more than 1.5 g for a Li-Ion cell and 8 grams for a Li-Ion battery
- The cell or battery must be of a type proven to meet the requirements of each test in the UN Manual of Tests and Criteria (see Section 16.5.2)
- Cells or batteries are separated or packaged in a manner to prevent short circuits and are packed in a strong outer packaging or are contained in equipment
- Except when contained in equipment, each package containing more than 24 lithium cells or 12 lithium batteries must be marked to indicate it contains lithium batteries, accompanied by special procedures to follow if the package is damaged, is capable of withstanding a 1.2 meter drop, and its gross weight does not exceed 30 kg (does not apply to cells or batteries packed with equipment)
- A written report is required to be submitted if a fire, violent rupture, explosion, or dangerous evolution of heat occurs

SP 189 – excepts medium lithium cells and batteries, including cells or batteries packed with or contained in equipment, from compliance with other requirements of Subchapter C, *Hazardous Materials Regulation*, provided the requirements of this provision are met. Requirements of this provision include:

- The equivalent lithium content is not more than 5 g for a Li-Ion cell and 25 grams for a Li-Ion battery
- The cell or battery must be of a type proven to meet the requirements of each test in the UN Manual of Tests and Criteria
- Cells or batteries are separated or packaged in a manner to prevent short circuits and are packed in a strong outer packaging or are contained in equipment
- Outside of each package is marked to indicate that cells or batteries are forbidden for transport aboard aircraft and vessels
- Except when contained in equipment, each package containing more than 24 lithium cells or 12 lithium batteries must be marked to indicate it contains lithium batteries, accompanied by special procedures to follow if the package is damaged, is capable of withstanding a 1.2 meter drop, and its gross weight does not exceed 30 kg (does not apply to cells or batteries packed with equipment)
- A written report is required to be submitted if a fire, violent rupture, explosion, or dangerous evolution of heat occurs

SP A54 – allows lithium batteries or lithium batteries contained or packed with *equipment* that exceed the maximum gross weight of 35 kg to be transported on cargo aircraft only if approved by the DOT Associate Administrator.

SP A55 – allows prototype lithium batteries and cells that are packed with not more than 24 cells or 12 batteries per packaging and have not completed UN testing to be transported by cargo aircraft if approved by the Associate Administrator and are: 1) transported in rigid outer packaging, and 2) each cell and battery is protected against short circuiting, surrounded by cushioning material, and individually packed in inner packaging that is placed inside outer specification packaging.

Packaging: Packaging requirements for Li-Ion batteries as prescribed in §173.185. There are two significant exceptions to the packaging requirements as discussed above in special provisions 188 and 189 and noted in Table 16-1.

Table 16-1. Rechargeable Li-Ion Cell/Battery Requirements by Size

Cell/Battery Maximum Equivalent Lithium Content	Shipping Classification	Testing Required	Special Packaging/Marking Requirements
1.5 grams/8.0 grams	Excepted/Not Class 9	UN T.1 – T.8	No
> 1.5 grams – 5.0 grams/ > 8.0 grams – 25.0 grams	Excepted/Not Class 9	UN T.1 – T.8	No
> 25.0 grams/ > 25.0 grams	Class 9	UN T.1 – T.8	Yes

Shipments for testing (prototypes) – A lithium cell or battery is excepted from each of the tests in the UN Manual of Tests and Criteria when transported by motor vehicle for purposes of testing. The cell or battery must be individually packed in an inner packaging, surrounded by cushioning material that is non-combustible and non conductive. The cell or battery must be transported as a Class 9 material. UN testing is further discussed in Section 16.5.2.

Quantity Limitations: See special provision A54 above.

16.3.3.2 Application for Special Permit or Party Status

A lithium cell or battery that does not comply with the special provisions of §172.102 or the packaging requirements of §173.185 may be transported only under conditions approved by the DOT Associate Administrator of Hazardous Materials Safety. An application for a special permit must be submitted at least 120 days before the requested effective date. The application must include:

1) a citation of the specific regulation from which the applicant seeks relief
2) specification of the proposed mode(s) of transportation
3) a detailed description of the proposed special permit (e.g., alternate packaging, test, procedure or activity)
4) proposed duration or schedule of events
5) basis for seeking relief

6) whether or not applicant is seeking emergency processing
7) identification and description of hazardous materials planned for transport
8) description of each packaging
9) documentation of quality assurance controls, package design, manufacture, performance test criteria, and in-service performance and service-life limitations

The application must demonstrate that a special permit achieves a level of safety at least equal to that required by regulation.

An applicant can also apply to be made party to an application or an existing special permit. Each application must include identification of the special permit application or special permit to which the applicant seeks to become a party and the applicants contact information. A party to a special permit is subject to all terms of that special permit.

16.3.4 Transportation Requirements for Military Air Shipments

The transport of Li-Ion batteries by military aircraft is not covered by DOT regulations. Transport by this means may be an alternative to ground transport for spacecraft containing Li-Ion batteries. Applicable requirements for military air shipments are contained in AFMAN-24-204, *Preparing Hazardous Materials for Military Air Shipments*. Key sections include those listed below.

- Attachment 2, Deviations, Waivers, and Special Requirements
- Attachment 4, Items Listing (similar to Table of Hazardous Materials and Special Provisions)
- Attachment 13, Class 9 – Miscellaneous Hazardous Materials
- A13.8, Lithium Batteries and Cells
- Attachment 14, Marking Hazardous Materials
- Attachment 15, Labeling Hazardous Materials

It is acceptable to use a Department of Defense (DoD) certification of equivalency, which is a certification that the proposed packaging equals or exceeds the requirements of 49 CFR 100-199, as authority for shipment by military air. A DOT exemption, which is the authority to deviate from the requirements of 49 CFR 100-199 (i.e., special permit or party status), can also be used as authority for shipment by military air. The test requirements prescribed in 49 CFR 173.185 must be met.

16.4 Design Safety Guidelines/Considerations

Consideration of appropriate design safety features must, first and foremost, meet the *general* safety criteria specified in AFSPCMAN 91-710 and NASA-STD-8719.24 which state “If a system failure may lead to a *catastrophic hazard*, the system shall have three inhibits (i.e., be dual fault/failure tolerant) and if a system failure may lead to a *critical hazard*, the system shall have two inhibits (i.e., be single fault/failure tolerant).” Secondly, *specific* Range Safety and DOT requirements applicable to the Li-Ion battery design and application being considered must also be met. When meeting safety requirements battery performance and mission assurance requirements (i.e., reliability, EEE parts, quality assurance, radiation effects, etc.) must also be considered to increase the likelihood of mission success. It is important that the project safety engineer work closely with systems engineering and battery and power subsystem design engineers early in the project life cycle to ensure that applicable safety requirements are identified, understood, implemented, and can be verified. Consideration of cell level, battery level, power subsystem level, and electrical ground support equipment level design safety features from those listed in Table 16-2, and discussed in subsequent paragraphs, must be a collaborative effort between system safety and the project team. Considerations should also include factors such as avoiding parasitic loads to minimize the amount of charge cycles required and to examine the possibility of not charging the battery after loading propellants.

Table 16-2. Design Safety Features

Feature	Protection Provided	Design Safety Considerations
CELL (note: a cell design safety feature can be credited as one inhibit against a catastrophic or critical hazard)		
☐ Positive Temperature Coefficient (PTC) Polyswitch	Temperature activated internal fuse protects cell from thermal damage due to external short circuits.	Reversible. Small cell application. Potential breakdown at high voltages.
☐ Current Interrupt Device (CID)	Internal disconnect provides overcharge protection and protects against short circuit cell failures.	Non-reversible. Renders corresponding series connected string open circuit. Results in reduction in battery capacity due to loss of string. Must be matched to cell chemistry. Small cell application.
☐ Shut Down Separator	Maintains isolation between electrodes. Interrupts flow of ions and halts cell chemical reaction in the event of external shorts, overcharge, and other thermal events.	Non-reversible. Renders corresponding series connected string open circuit. Results in reduction in battery capacity. Small and large cell application. Have not proven to be 100% effective. Should be used with other cell safety features.
☐ Pressure Relief	Burst disc releases internal pressure in a safe and controlled manner preventing potential rupture or explosion of the cell.	Unlikely to activate during normal fault conditions. Overcharge protection mechanism (CID) would activate prior to venting. Small and large cell application.
☐ Cell Voltage Monitoring	Indicates overcharge conditions and need to initiate response actions.	Most assured method of detecting individual cell overcharge. Removes potential for uncertain knowledge of cell balance state. Typical in batteries that have cell balancing electronics. Can support possibility of response actions at the cell level. Large cell application. Difficult to implement for small cell batteries with many cells.
☐ Case Mechanical Design	Provides controlled cell venting. Prevents physical damage to cell resulting in internal shorts and thermal runaway.	Case design dependent on cell chemistry and potential pressure increases.

Feature	Protection Provided	Design Safety Considerations
CELL (note: a cell design safety feature can be credited as one inhibit against a catastrophic or critical hazard)		
BATTERY		
☐ Topology (Large Cells vs. Small Cells)	Determines amount of energy released during catastrophic failure (large cells can release larger quantities of energy).	Potential propagation of a cell failure to surrounding cells due to thermal effects greater is greater for large cell designs.
☐ Connect/Disconnect Switch	Provides spacecraft and ground support equipment connect/disconnect capability.	In disconnected state provides safer battery integration to spacecraft (elimination of hot mates) and eliminates effects of external short circuits. Can protect battery from over- discharge and degradation during on-orbit spacecraft power outages.
☐ Fuse	Protects battery against external shorts occurring during ground processing and on-orbit operations.	Non-reversible. Generally required for human rated missions. For single battery architecture a blown fuse results in loss of mission.
☐ Cell Matching	Minimizes cell divergence and potential overcharge conditions.	Tight matching can assure cell balance and reduce the need for cell balance electronics. Life testing is used to validate cell balance.
☐ Management Electronics (protection electronics)	Protects against a variety of electrical abuse scenarios including over voltage overcharge, over current overcharge, external short circuit, over-discharge, and imbalance protection.	Can be packaged within battery or separate from battery. Not typically implemented for small cell batteries with many cells.
☐ Cell Monitoring Electronics		
☐ Cell Balancing Electronics		
☐ Voltage Monitoring	Indicates overcharge conditions and need to initiate response actions.	Can be provided to monitor voltage of a virtual cell (i.e., multiple cells connected in parallel) or voltage of battery. Requires balanced cells. Does not detect which cell or cells are overcharged.
☐ **Temperature Monitoring**	Indicates over temperature conditions the need to initiate response actions.	Temperature sensors should be located to indicate representative cell temperatures (hottest cells, coldest cells, and center of battery).
☐ Cell Bypass	Isolates a failed cell or virtual cell.	Large cell application when cells do not have internal overcharge protection. Not typically implemented for small cell batteries with many cells.
☐ Thermal Conductivity	Provides cell and battery heat dissipation.	Selection of materials with good thermal conductivity properties.

Feature	Protection Provided	Design Safety Considerations
CELL (note: a cell design safety feature can be credited as one inhibit against a catastrophic or critical hazard)		
☐ Vent Gas Ignition Suppression	Prevents flammable vent gases, oxygen, and an ignition source from combining resulting in fire or explosion.	Primarily includes methods to reduce shorting and sparking conditions.
☐ Case Mechanical Design	Allows cell vent gases to benignly escape/disperse. Prevents physical damage to cells resulting in internal shorts and thermal runaway.	Battery cases are not typically sealed and should be designed to allow the venting of multiple cells simultaneously.
POWER SUBSYSTEM		
☐ Arming Plug	Removal isolates battery from spacecraft harness during ground integration and testing.	Can be credited as an inhibit against a catastrophic or critical hazard.
ELECTRICAL GROUND SUPPORT EQUIPMENT		
☐ Fuse/Circuit Breaker	Protects battery against external shorts.	Fuses can be included as part of the battery charging/discharging EGSE and/or included in a test cable connected between the battery and the battery charging/discharging unit or between the battery and spacecraft harness.
☐ Battery Monitoring	Provides overcharge protection.	Supports action (autonomous or operator controlled) to stop battery charging if an overvoltage or over temperature condition exists. Electrical ground support equipment used for battery charging and discharging should be dedicated to the power subsystem/battery architecture.

16.4.1 Cell Level Design Safety Features

There are a variety of cell-level safety design features that protect against internal and external short circuits, thermal runaway, and cell overcharge conditions. A brief overview of these cell design features is provided below including a description, a discussion on how they operate, what they protect against, and when to consider them in cell design.

Positive Temperature Coefficient Polyswitch: A Positive Temperature Coefficient (PTC) polyswitch protects a battery cell against thermal damage to the cell arising from long-duration high-current discharges (e.g., an external short circuit to the cell causing an overcurrent hazard). The PTC circuit is typically a composite of semi-crystalline polymer and conductive particles. At low temperatures, the conductive particles form a low resistance path through the polymer. As temperatures increase past a transition or threshold temperature, the polymer’s crystalline melts and expands disturbing the low resistance paths and increasing the PTC resistance. During an excessive discharge, heat is generated in the PTC polyswitch material and this causes the PTC to self-heat. Its resistance increases sharply reducing the current flow to a steady state value in which most of the cell voltage is across the PTC but the current is significantly reduced. As long as the short is maintained, the PTC produces enough heat to keep itself in this “tripped” state in which lower current is offset by greater voltage drop across the PTC. The PTC device cools once the current flow has been interrupted, and its resistance will return to approximately its normal low-level.

Design Safety Considerations: The PTC makes a good short circuit protection mechanism that can prevent thermal damage to the cell and possible thermal runaway. PTC activation and limited current level is dependent on temperature, current, and time. Short duration high current draws are generally not affected. PTC activation is reversible as temperature and current falls but typically results in a small increase in resistance. PTCs are typically used on small battery cells, such as the Sony 18650 cell, connected in a series-parallel configuration. PTCs are effective on up to eight cells connected in series. However, for strings that are longer than 8 cells in series, PTCs may experience voltage breakdown when the string is short circuited. The use of bypass diodes can be used to avoid PTC breakdown.

Current Interrupt Device: If a cell is overcharged a permanent chemical breakdown within the cell leads to gas generation and an increase in cell internal pressure. The pressure causes a pressure tight internal disk to distort and bow and physically break an electrical connection between the cell cathode and the positive terminal of the cell. This shuts off current flow and renders the cell open circuit preventing further potentially dangerous overcharge. This disconnect protection mechanism is not reversible and constitutes an open-circuit failure of the cell. The protection mechanism is often referred to as the current interrupt device (CID). Although CIDs are pressure activated they are sensitive to temperature. Higher cell temperatures will lead to higher pressures more quickly. Extreme cell operating temperatures can cause the same chemical breakdown and gas generation. Activation of a CID can be caused by faulty battery charge management raising cell voltage above 4.2V on average or cell divergence and an end of charge voltage combining to push one or more cells above 4.2V. The battery cell is designed to remain sealed if the CID is activated.

Design Safety Considerations: The CID provides cell overcharge protection. If activated, it safely disconnects the cell from the corresponding series connected string minimizing the possibility of thermal runaway and cell venting. A CID can also protect against short circuit cell failure. If a short circuit cell failure were to occur, the remaining cells in the string would overcharge and a CID would activate on one of the over-charged cells in the string. The string would then be rendered open circuit. Loss of a string would result in a reduction in capacity of the battery. The reduction is based on the battery S-P topology. If CIDs were to activate in each battery string the battery should shut down safely minimizing thermal runaway, venting and catastrophic failure. However, at high overcharge rates, temperatures can continue to rise after disconnection resulting in possible venting and catastrophic failure. CIDs must be appropriately matched to cell chemistry so that overcharge conditions result in sufficient gas generation to activate the CID prior to thermal runaway occurring. CIDs are typically only used on small battery cells, such as the Sony 18650 cell, connected in a series-parallel configuration.

Shut-Down Separator: A shut-down separator provides an isolating layer between the anode and cathode of the battery cell and is a microporous separator. In the event of a very fast overcharge, or other independent thermal event, where the cell temperature exceeds a predetermined temperature, the separator micropores soften and close preventing the flow of ions, thereby halting the cell chemical reaction.

Design Safety Considerations: Shut-down separators protect against elevated cell temperature resulting from external short circuits, overcharge, or abuse conditions. Shut down of a cell is a permanent condition. Similar to activation of a CID, the corresponding series connected string would be rendered open circuit resulting in a reduction in the capacity of the battery.

Pressure Relief: A controlled cell vent mechanism releases internal pressure in a safe and controlled manner preventing an uncontrolled rupture or explosion of the cell case when under moderate abuse conditions. Cell venting is unlikely to occur even under extreme fault conditions in the space environment. Typically pressure relief devices should be set to operate at 1.5 times the normal cell operating pressure.

Design Safety Considerations: During moderate abuse conditions the pressure may continue to rise in a cell, even after a disconnect mechanism operates (i.e., CID), if the cell is severely abused, for example, thrown onto a fire. Under "normal" fault conditions, such as overcharge resulting from test equipment failure, or in tests to destruction, the cell overcharge protection mechanism would disable the cell without controlled venting occurring. Vent pressure is typically higher than the CID activation pressure and lower than the cell burst pressure. This ensures that the CID activates before the vent disk ruptures and the vent disk ruptures before the cell can explode. The cell pressure is therefore released in a "leak before burst" controlled manner.

Cell Voltage Monitoring: Monitoring the voltage of individual battery cells is the best method for detecting an overcharged cell. Individual cell voltage monitoring removes the potential uncertainty of the cell balance state. Range safety requires that individual cell monitoring and recording be performed during charging and discharging. Cell voltage monitoring is discussed in Section 9.2.1.1.

Design Safety Considerations: Individual cell voltage monitoring is not practical for small-cell batteries that can consist of tens or hundreds or individual cells. Although Range Safety requires individual cell monitoring during charging and discharging, monitoring across series connected strings or across virtual cells (i.e., multiple cells connected in parallel) is an acceptable monitoring method provided battery cells are matched and balanced. Appropriate battery monitoring during charging and discharging should be discussed with and approved by Range Safety.

Case Mechanical Design: The cell case should be designed to a factor of safety that precludes case rupture prior to cell case venting occurring. Typically the minimum burst factor of safety for a cell is 1.5.

Design Safety Considerations: Cell case design protects against overpressure conditions preventing cell rupture or explosion and to a lesser extent physical damage to the cell that can result in internal shorting.

16.4.2 Battery Level Design Safety Features

There are a variety of battery-level safety design features that protect against internal and external short circuits, thermal runaway, battery overcharge conditions, and physical damage to the battery. A brief overview of these battery design features is provided below including a description, a discussion on how they operate and what they protect against, and when to consider them in cell design.

Topology (large format cells versus small cells): Large format cells contain a larger quantity of energy than small cells. Therefore, if catastrophic failure of a cell occurs, a larger quantity of energy is potentially released leading to a more hazardous situation. Topology is discussed in Section 10.5.

Design Safety Considerations: If appropriate safety features are incorporated into the power subsystem design, consisting of battery cells, battery, electrical ground support equipment, and operations, the selected battery cell size would not be a significant safety concern. Incorporation of both cell and battery level design safety features is dependent on cell size and electrical configuration of the battery (e.g., series connected, series-parallel connected, or parallel-series connected).

Connect/Disconnect Switch: One or more switches (typically latching relays) can be used on the battery output to disconnect the battery from all spacecraft loads during on-orbit power outages to prevent over-discharge and possible degradation to the battery. Battery connect and disconnect is discussed in Sections 12 and 13.

Design Safety Considerations: Having the ability to disconnect the battery from its external connectors eliminates the need for hot mates and the possibility of external shorts during electrical integration to the spacecraft. Disconnection of a battery in a multiple battery architecture while on-orbit allows a degraded battery to be isolated from the power subsystem. For single battery architectures, disconnecting the battery while on-orbit results in a dead bus configuration. Mission success and safety should both be considered before incorporating disconnects switches.

Fuse: Fuses can protect the battery from external shorts that can occur in the power subsystem or electrical ground support equipment.

Design Safety Considerations: Preventing short circuits during spacecraft integration can prevent a number of battery failures that could result in fire or explosion. If a fuse were to trip during on-orbit operations, the battery (there may be multiple batteries) would be rendered open circuit and not reversible. Mission success and safety should both be considered before incorporating fuses.

Cell Matching: Cell matching must be performed regardless of the battery chemistry chosen or the qualification/acceptance testing to be performed. Various screening and matching methods are typically utilized during lot acceptance testing to match cells with similar capacity, end of charge resistance/impedance, end of discharge resistance/impedance, and self-discharge rates. Cells are matched based on minimization of capacity spread.

Design Safety Considerations: Cell matching processes can be used to support the assertion that significant cell divergence will not occur during the spacecraft mission and therefore cell balancing hardware is not necessary.

Management Electronics (Protection Electronics): Li-Ion batteries may require relatively complex protection circuitry to protect against a variety of electrical abuse scenarios including over voltage overcharge, over current overcharge, discharging at an excessive current (external short circuit), over-discharge, and imbalance protection for multi-series battery assemblies.

- **Cell Monitoring Electronics:** Maximum charge voltage for a Li-Ion cell varies depending on the specific battery chemistry or the intended use environment (4.2 V is typical for most chemistries). Preventing overcharge is considered sufficiently critical to warrant individual monitoring of cells or series element voltages by electronics to prevent any cell from exceeding a voltage limit. In addition, most protection electronic packages include multiple independent circuits to terminate charge so that a single-point circuitry failure cannot disable over-voltage protection. Cell monitoring is discussed in Section 9.

  Design Safety Considerations: Cell monitoring electronics add complexity, cost, and mass to overall battery design.

- **Cell Balancing Electronics:** In multi-series element battery assemblies, cells in the various series elements may not age uniformly, resulting in divergent capacities among series elements. Individual series element voltage sensing is used to prevent over charge or over-discharge of any element. However, a significant imbalance can indicate a problematic cell, or lead to over current damage of a high impedance series element. Cell balancing is discussed in Section 10.0.

  Design Safety Considerations: Cell balancing electronics are typically used for large cell batteries connected in a single series configuration and less commonly used for small cell batteries connected in series-parallel. For parallel-series batteries they may be used when high reliability is required. Battery life testing can determine how well battery cells remain balanced and whether or not cell balancing electronics are necessary.

- **Voltage and Temperature Monitoring:** Battery-level voltage monitoring can be accomplished across a group of cells connected in series, across a virtual cell (i.e., multiple cells connected in parallel), or for the entire battery to provide an indication of a cell overcharge. Temperature monitoring can indicate the onset of thermal damage from a variety of reasons including internal and external short circuits and over charge conditions.

  Design Safety Considerations: Monitoring battery voltage can detect a battery overvoltage condition but will not indicate which cell or cells are overcharged. The most effective way to monitor for cell overcharge conditions is to monitor individual cell voltages. If this cannot be accomplished monitoring across a group of cells connected in series or across virtual cells may be an acceptable monitoring method provided the battery cells are matched and balanced. The least effective method of detecting cell overcharge is monitoring the voltage across the entire battery. Appropriate battery monitoring should be discussed with and approved by Range Safety. Battery voltage monitoring is discussed in Section 9.2.1.2. Temperature sensors should be located to accurately indicate cell temperatures.

Cell Bypass: Battery cell bypass isolates a failed battery cell or virtual cell and provides an alternate high current path for battery charge and discharge thus eliminating single point failures within the battery. Cell bypass is discussed in Section 11.

Design Safety Considerations: Bypassing a Li-Ion battery cell with a high SOC, by applying a short across it, is hazardous and should be avoided. Cells should only be bypassed at a low SOC. Bypass circuitry should be fault tolerant to avoid unintended cell bypass. For parallel-series connected batteries, in which cells may not have internal overcharge protection, (virtual) cell monitoring is essential and cell bypass is necessary to remove a virtual cell with a failed open cell from the battery before a cell overcharge condition occurs. Cell bypass capability is not included in small cell series-parallel connected batteries because individual cells have internal overcharge protection (i.e., a CID) and the battery has multiple series strings. Any single cell failing open will lead to loss of one string. A single cell failing short will eventually lead to cell overcharge in the string. The overcharge protection circuit will open and detach the cell string from the battery. Loss of a single string does not appreciably reduce the capacity of the battery.

Thermal Conductivity: The first stage of catastrophic failure at the battery level is cell venting. Cell venting is sensitive to operating temperature. If cell temperature can be kept below the lowest vent temperature, the risk of venting, and therefore probability of catastrophic failure can be eliminated. The ability to remove heat from the cells should be maximized. Thermal configuration is discussed in Section 7.2.4.

Design Safety Considerations: Design features that can increase thermal conductivity and heat dissipation include thermally conductive battery case structure, thermally conductive cell mounting plates, brackets, piece parts and other materials, and thermal radiators. Thermal analysis should account for maximum heat dissipation during ground charging/discharging.

Vent Gas Ignition Suppression: Vent gas ignition requires the presence of vented gases, oxygen, and an ignition source (e.g., a spark). Prevention of vent gas ignition can be achieved by eliminating ignition sources and physically separating vented gases, oxygen and ignition sources.

Design Safety Considerations: Some methods that can be employed in the battery design include minimizing arcing paths via component spacing, use of insulative coatings on cell interconnections, and establishing vent paths that control the release of vent gases (e.g., vented battery case that allows cell venting to be dispersed). The surfaces of battery terminals on the outside of the battery case need protection from accidental bridging. Battery terminals which pass through metal battery cases should be insulated from the case by an insulating collar or other effective means. The surfaces of battery terminals that extend inside the battery case need to be insulated with potting materials to prevent unintentional contact with other conductors inside the case and also to prevent bridging by electrolyte leaks. Wires inside the battery case should be insulated, restrained from contact with cell terminals, protected against chafing and physically constrained from movement due to vibration or bumping. Internal shorts are caused by metallic burrs, misalignment, separator failure, or other means of direct contact between the positive and negative materials inside a battery cell.

Case Mechanical Design: If sealed, the battery case should be designed to a factor of safety that precludes case rupture prior to case venting occurring. An ultimate factor of safety of 3:1 is required based on worst case pressure buildup for normal operations.

Design Safety Considerations: Battery case design protects against overpressure conditions preventing case failure. It also provides structural integrity during all vibration and shock environments including those during spacecraft handling and transportation. To prevent shorts between leaked electrolyte and the battery case, all inner surfaces of metal battery cases typically have either an anodized finish or are coated with a non-electrically conductive, electrolyte resistant finish.

16.4.3 Power Subsystem Design Safety Features

Battery charging flight hardware is required to be current limited by design and provide protection and monitoring to prevent battery damage or failure. It is required by Air Force Range Safety to be two fault tolerant against each battery cell exceeding 4.4 volts and discharging to less than 0 volts. It must actively monitor each cell and limit the charge/discharge rate to prevent high heat or internal sparking that could create thermal runaway. A temperature monitoring system should be used in addition to other methods of charge control to protect the battery. Additional power subsystem features may include:

Battery Arming Plug: utilized to isolate the battery from spacecraft loads during ground processing to preclude battery discharge. The arming plug is typically integrated into the spacecraft harness design.

Design Safety Considerations: Can be credited as an inhibit against a catastrophic or critical hazard during ground processing.

16.4.4 Electrical Ground Support Equipment (EGSE) Design Safety Features

Battery charging equipment must be two fault tolerant against each battery cell exceeding 4.4 volts and discharging to less than 0 volts. It must actively monitor each cell and limit the charge/discharge rate to prevent high heat or internal sparking that could create thermal runaway. Voltage monitoring and recording at the cell, virtual cell, or battery level is necessary during charging and discharging. Charge voltages are required by range safety to be recorded periodically from 10 seconds to 2 minute intervals based on charge rates. EGSE must also be intrinsically safe, if required, and prevent high heat, sparking, and high charge/discharge current rates. EGSE features include:

Fuse: Fuses (or circuit breakers) should be included in all EGSE used for battery charging and discharging to protect the battery against shorts that may occur in the EGSE. A fused test cable can also be utilized to protect against external short circuits occurring in EGSE or elsewhere within the power subsystem during ground testing.

Design Safety Considerations: Can be credited as an inhibit against a catastrophic or critical hazard during battery charging and discharging.

16.5 Battery Safety Testing

Requirements for Li-Ion battery safety testing are primarily driven by Air Force Range Safety and Department of Transportation requirements. Battery-level safety needs to be validated by test under all known failure modes, which include at a minimum the following conditions: -overcharge, over-discharge, over-temperature, over pressurization, internal cell short and external cell short. Cell level, element-level, or battery-level development testing that simulates battery mechanical and thermal design needs to evaluate the potential of one cell failure propagating to another cell or piece part within the battery. Safety tests should be conducted over a range of operating conditions that exceed the design limits to identify marginal capabilities and marginal design features.

16.5.1 Range Safety Testing

Flight battery cell and battery case qualification tests are required to be conducted on flight quality batteries to demonstrate structural adequacy of the design. Qualification tests ensure the battery can withstand ground environments during transportation, storage, and processing. The following testing is required.

Pressure Testing: Pressure testing is used to verify the vent operates as intended and that the vent is adequately sized to prevent cell/battery fragmentation. The test is done at the battery level if the battery is sealed; otherwise it is done at the cell level. A pressure cycle test of the battery cell followed by burst testing can be used to validate structural integrity of the cell and burst factor of safety.

Lithium Battery Constant Current Discharge and Reversal Test: A constant current discharge and reversal test determines if the pressure relief mechanism functions properly or case integrity is sustained under circumstances simulating a high rate of discharge. Testing criteria is specified in AFSPCMAN 91-710.

Lithium Battery Short Circuit Test: A short circuit test determines if the pressure relief mechanism functions properly under conditions simulating a battery short circuit failure mode. If a pressure relief mechanism is not provided, lithium battery case integrity must be determined under conditions simulating a battery short circuit failure mode. Testing criteria is specified in AFSPCMAN 91-710.

Lithium Battery Drop Test: A lithium battery drop test is required to demonstrate that the battery, in an activated state, does not vent or start a hazardous event when dropped from a 3-foot height to a concrete pad on the edge of the battery, on the corner of the battery and on the terminals of the battery.

16.5.2 Department of Transportation (DOT)/United Nation (UN) Testing

The transportation requirements in 49 CFR 173.185, *Lithium Cells and Batteries*, require that Li-Ion cells and batteries are of a type proven to meet the requirements of each test in the *Recommendations on the Transport of Dangerous Goods – Manual of Tests and Criteria*. It is important that testing requirements and success criteria are shared with cell and battery design engineers early in the project life cycle to ensure that the designs will meet the testing requirements. Table 16-3 summarizes the UN testing and indicates the number of cell and battery samples required to be subjected to each test.

Table 16-3. UN Battery Testing Requirements Number of Samples

This table indicates the number of cells that must be subjected to the various tests.	Altitude	Thermal Test	Vibration	Shock	External Short Circuit	Impact/ Crush	Overcharge	Forced Discharge
	T.1	**T.2**	**T.3**	**T.4**	**T.5**	**T.6**	**T.7**	**T.8**
CELL								
Rechargeable Cells								
1st cycle, charged	10					--	N/A	--
1st cycle, fully discharged	--					--		10
1st cycle, 50% discharged	--					5		--
50 cycles, fully discharged	--					--		10
BATTERY								
Small Rechargeable Batteries (≤ 12 kg)								
1st cycle, fully charged	4					N/A	4	N/A
50 cycles, ending fully charged	4						4	
Large Rechargeable Batteries (> 12 kg)								
1st cycle, fully charged	2					N/A	2*	N/A
25 cycles, ending fully charged	2						2*	
BATTERY ASSEMBLIES whose cells and modules have passed UN/DOT 38.3 testing								
Rechargeable Batteries up to 6200 Wh or 500 g lithium metal	N/A		1			N/A	1	N/A
Rechargeable Batteries over 6200 Wh or over 500 g lithium metal (if has battery management system protection)	N/A					N/A	N/A	N/A

* May use the same samples for tests T.1 –T.5 if undamaged. Otherwise, will require new samples.

Tests T.1 to T.5 can be conducted in sequence on the same sample, tests T.6 and T.8 can be conducted using not otherwise tested samples, and Test T.7 may be conducted using undamaged samples previously used in Tests T.1 to T.5 for purposes of testing on cycled batteries. The success criteria require that the samples do not result in leakage, venting, disassembly, rupture or fire when subjected to testing. Additional details on test procedures and success criteria can be found in the *Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria* published by the UN.

16.6 Operational Safety Considerations

The typical life cycle of a Li-Ion battery for spacecraft applications is comprised of multiple steps including:

- Cell manufacturing and initial testing at the manufacturing facility.
- Cell manufacturer shipment to battery assembler or manufacturer.
- Battery assembler or manufacturer combines multiple cells, protection electronics, and case materials to create a battery. Cell-level and/or battery-level testing may occur at this facility.
- Battery assembler or manufacturer ships the battery to spacecraft manufacturer for integration and testing. Battery-level testing and/or conditioning may occur at this facility.
- Spacecraft manufacturer mechanically and electrically integrates battery onto spacecraft and performs integration testing with spacecraft. Battery charging and discharging via spacecraft power subsystem and/or EGSE typically occurs.
- Spacecraft manufacturer ships the battery, usually contained in the spacecraft, to launch site for processing. Although there are range safety requirements related to Li-Ion battery storage and disposal while at the launch site, these activities are typically not necessary. Battery conditioning may occur at this site.
- Spacecraft is launched aboard an expendable launch vehicle to begin mission.

There are specific hazards associated with each of these steps. The safety of personnel and hardware must be assured throughout all phases of battery development, fabrication, assembly, testing, transportation, and launch site processing. Development and use of approved procedures or work instructions helps mitigate operational hazards. Procedures and work instructions should include a description of the operation(s) being performed, identification of required Personal Protective Equipment (PPE), personnel training requirements, detailed steps to be performed, proper warnings, cautions and notes, and emergency actions to be taken in the event of a hazardous situation.

16.6.1 Cell and Battery Manufacturing, Assembly and Testing

The primary hazards during manufacturing, assembly, and testing include venting of toxic materials/gases, electric shock/burns, and fire/explosion due to internal or external shorting of cells or batteries. General safety precautions that control these hazards include:

- Safety glasses should be worn at all times. All jewelry should be removed so that cells or the battery are not inadvertently shorted.
- Cells received from the manufacturer should remain in their original containers until they are to be assembled into the battery.
- Once cells are removed from original packaging they should be arranged/handled to preclude shorting.
- Cells and batteries should be treated as always have a voltage potential and therefore connection or disconnection is considered an electrical personnel hazard and a spark potential.
- Cells should not be placed on electrically conductive surfaces. All work surfaces should be constructed with non-conductive materials.

- No cell should be allowed to discharge below the minimum voltage limits or charge above the maximum voltage limits recommended by the manufacturer.
- Cells should be transported in non-conductive carrying trays to reduce the chances of cells being dropped causing shorting or other physical damage.
- Dented or damaged cells or batteries should be disposed. Denting of sides or ends increases the likelihood of developing internal short circuits.
- Soldering directly to the cell case should be avoided. Only solder to the solder tabs welded to the case.
- Loose wires should not be stripped until it is time to install a connector. If no connector is used, wire ends should be insulated.
- If leads or solder tabs need to be shortened or leads need to be tinned, do only one wire at a time.
- Cells should not be forced into battery housings/cases, which could deform the battery cell or case resulting in internal short circuits. Check for proper fit before inserting cells into cases.
- All batteries should be labeled with the appropriate warnings as they appear on the cell label.
- Certain potting compounds are exothermic (release heat) when they set. It is important that the maximum temperature of the cell is not exceeded during the potting process.
- Tools should be made from, or covered with, non-conductive materials

Additional considerations during cell and battery manufacturing, assembly, and testing include the need to establish emergency procedures that address incident response, first aid, and cleanup, facility requirements, formation of flammable gases, and personnel exposure to toxic electrolyte that can cause irritation to the respiratory tract, eyes, and skin. Venting can result in the release of hazardous air contaminants, including corrosive or flammable vapors. Review of applicable Material Safety Data Sheets (MSDSs) or product information sheets should be performed prior to working with cells and batteries so that the steps to take in the event of a release are understood.

16.6.2 Spacecraft Assembly, Integration, and Testing (AI&T)

Mechanical and electrical integration occurs at the battery level during spacecraft assembly. The primary hazards to consider during spacecraft assembly and integration include physical damage to the battery, electric shock/burns during electrical connection, and external short circuits. Hazards during testing, which typically includes charging and discharging the battery, are overcharge, over-discharge, high temperatures, fire, and explosion. General safety precautions that control these hazards include:

- Use of overhead crane and handling equipment (lifting fixture, sling, etc.) to install batteries that cannot be easily installed manually.
- Use of a battery arming plug that can be removed to isolate the battery from the spacecraft power bus while electrically connecting the battery.
- Matching voltages and currents when “hot” mating the battery to the spacecraft power bus or installing the battery arming plug.
- Use of “Safe to Mate” process/procedures for electrical connections.

- Use of approved and certified EGSE for battery charging/discharging that protects the battery from external short circuits within the EGSE.
- Actively monitor cell, virtual cell, or battery voltages during charging and discharging.

16.6.3 Transportation

The primary hazards associated with transportation of cells and batteries, either separately or contained within a spacecraft, include physical damage, external short circuits, high temperatures, fire, and explosion. General safety precautions that control these hazards include:

- Package, label, and transport batteries in accordance with DOT requirements, specifically 49 CFR §173.185, Lithium Cells and Batteries.
- For batteries contained in equipment, i.e., integrated with a spacecraft, they must:
  - Be a type proven to meet the requirements of each UN Manual of Tests and Criteria (see Section 16.5.2.).
  - Incorporate a safety venting device or otherwise be designed in a manner that precludes violent rupture under conditions normally incident to transportation.
  - Be equipped with an effective means to prevent dangerous reverse current flow if the battery contains cells or series of cells connected in parallel.
  - Be provided with an effective means of preventing short circuits.
  - Contained in equipment that is packed in strong outer packaging that is waterproof. The equipment and batteries must be secured within the outer packaging and be packed to prevent movement, short circuits, and accidental operation during transport.
- Cells and batteries that do not comply with the provisions of 49 CFR §173.185, i.e., have not undergone UN transportation testing; can only be shipped with approval from the DOT Associate Administrator of Hazardous Materials Safety.

16.6.4. Launch Site Processing

The primary hazards associated with launch site processing are those related to “conditioning” the battery at the processing facility and/or launch pad including: overcharge, over-discharge, high temperatures, fire, and explosion. General safety precautions to consider that control these hazards include:

- Use of approved and certified EGSE for battery charging/discharging that protects the battery from external short circuits within the EGSE.
- Actively monitor cell, virtual cell, or battery voltages during charging and discharging.
- If included in the design, installation of the battery arming plug as late in the launch countdown as practical.

16.7 Safety Compliance/Certification

Safety compliance and certification is achieved through a combination of requirements compliance, safety analyses, safety data submittals, and approvals from various competent authorities (i.e., project safety engineer, customer safety, DOT Associate Administrator, Range Safety, etc.).

16.7.1 Requirements Compliance

Utilizing a checklist of all design, test, analysis, and data submittal requirements is an effective means to document safety requirements. Safety requirements compliance is achieved by identifying for each requirement, if the proposed design is compliant, non-compliant but meets intent, non-compliant, or non-applicable. A compliance checklist should also include a resolution of how each requirement has been dispositioned and a verification reference. It should be noted that AFSPCMAN 91-710 allows tailoring (deletions, changes, or additions) of range safety requirements provided an equivalent level of safety can be achieved. The requirements checklist should be shared with design and operations personnel early in the power/battery subsystem development life cycle to ensure requirements will be met. Later in the life cycle the checklist provides documented evidence of compliance.

16.7.2 Safety Analysis

There are various safety analyses that can be utilized to effectively assess the safety of the Li-Ion based power subsystems.

Preliminary Hazard Analysis - A PHA is a qualitative hazard identification and frequency analysis technique used to assess potential hazards at an early design stage. The PHA identifies hazards, their associated causal factors, effects, level of risk, necessary hazard control strategies, and follow-on actions. It provides a methodology for identifying and collating hazards in the Li-Ion based power subsystem and can be used to establish the initial system safety requirements for design from preliminary and limited design and operations information. A PHA can be formatted as a table with columns for general hazard cause, hazard description, causal factors, probability, consequence, risk index, and initial hazard assessment including a discussion on probability and consequence determinations and proposed hazard mitigation.

Subsystem Hazard Analysis (SSHA) – A SSHA verifies subsystem compliance with safety requirements contained in subsystem/system specifications and other applicable documents. The SSHA identifies hazards associated with the design of the Li-Ion based power subsystem including component (i.e., cell, battery, power subsystem) failure modes, critical human error inputs, and hazards resulting from functional relationships between components and equipment comprising the subsystem (e.g., EGSE). The SSHA recommends actions to eliminate identified hazards or control their associated risk to acceptable levels. The SSHA should assess the adequacy of the Li-Ion based power subsystem design safety features. Results of the SSHA should be documented in a hazard report and/or safety data package (see Section 16.7.3)

Operating and Support Hazard Analysis (O&SHA) - An O&SHA identifies and evaluates hazards resulting from the implementation of operations or tasks performed by persons, considering the following criteria: the planned system configuration and/or state at each phase of activity; the facility interfaces; the planned environments or the ranges thereof; the supporting tools or other equipment, including software controlled automatic test equipment specified for use; operational and/or task sequence, biotechnological factors, personnel safety and health requirements; and the potential for unplanned events including hazards introduced by human errors. The O&SHA identifies the safety requirements or alternatives needed to eliminate or control identified hazards or to reduce the associated risk to acceptable levels. The O&SHA should assess hazards associated with spacecraft AI&T, transportation, and launch site processing. Results of the O&SHA should be documented in a hazard report and/or safety data package (see Section 16.7.3)

Because general safety design policy requires the Li-Ion based power subsystem to be fault/failure tolerant based on hazard consequences, Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) are effective in assessing compliance. Application of each is discussed below.

FMEA – A procedure by which each potential single component failure mode in the Li-Ion based power subsystem can be analyzed to determine the results or effects on the system and to classify each potential failure mode according to its severity. An FMEA is very effective in evaluating failure modes associated with battery cells and cell safety components such as PTCs, CIDs and vents; battery level safety components such as battery management electronics, relays, and fuses; and EGSE safety components including electronics, fuses, and software.

FTA – A graphic method of safety analysis by which possibilities of occurrence of specific adverse events are investigated. After selection of an adverse event (e.g., Li-Ion battery rupture/explosion/ fire), all factors, conditions, events, and relationships that could contribute to that event are indicated. Single component failures identified in an FMEA can be inputted to the FTA as basic initiating events. By determining the fault tree minimal cut sets (i.e., the smallest combination of component failures, which if they occur, will cause the adverse event to occur) the Li-Ion based power subsystem fault/failure tolerance can be determined.

16.7.3 Safety Data Submittals

Hazard Reports – Hazard reports are prepared to further analyze hazards categorized in the PHA as catastrophic or critical or those having an unacceptable risk index. Hazard reports should include an initial (unmitigated) risk index, hazard title/description, applicable safety requirements, identified hazard causes, credited hazard controls, verification of hazard controls, a final (mitigated) risk index, and closure status.

Safety Data Package – A safety data package such as a Missile System Prelaunch Safety Package (MSPSP) or Safety Assessment Report (SAR) is a documentation data submittal that provides detailed description of hazardous and safety critical flight hardware and ground support equipment. The safety data package is one of the media through which safety approval (from Range Safety) to process the spacecraft at the launch site is obtained. It should include results from the various safety analyses that were performed. For Li-Ion based power subsystems the following battery-specific data should be included in the safety data package:

- Design versus actual operating parameters of cells and batteries
- Cell chemistry and physical construction
- Cell and battery case design
- Physical and electrical integration of cells that form the battery
- Battery size and weight
- Cell vent parameters
- Toxic chemical emission of cells and evaluation of hazards
- EPA and DOT classification of battery
- Description of cell, battery, power subsystem, and EGSE safety devices
- Description of all operations including packing, transportation, activation, installation, checkout, charging, and usage

- Identification of hazards associated with all operations and the safety controls in effect
- Manufacturing qualification and acceptance testing results
- Specification of the system that uses the battery
- Description of EGSE
- List and summary of test plans and procedures

17. References

Reference 1: *“Space Mission Engineering: The New SMAD”*.

Reference 2: 2005 NASA Battery Workshop, “Quallion Technology,” by H. Tsukamoto, December 2005

Reference 3: 2012 NASA Battery Workshop, “Capacity Recovery in Lithium-Ion Cells,” by Albert Zimmerman, November 2012