

CREWED SPACE VEHICLE BATTERY SAFETY REQUIREMENTS

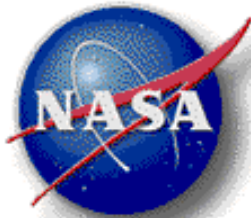
Engineering Directorate
Propulsion and Power Division

Availability:

Public Release Statement:

This document has been reviewed for Proprietary, SBU, and Export Control (ITAR/EAR) and has been determined to be nonsensitive. It has been released to the public via the NASA Scientific and Technical Information (STI) Process DAA JSC 40389.

March 2017
Revision D



National Aeronautics and
Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

PREFACE

The Crewed Space Vehicle Battery Safety Requirements document has been prepared for use by designers of battery-powered vehicles, portable equipment, and experiments intended for crewed spaceflight. The purpose of the requirements document is to provide battery designers with information on design provisions to be incorporated in and around the battery and on the verification to be undertaken to demonstrate a safe battery is provided. The term "safe battery" means that the battery is safe for ground personnel and crew members to handle and use; safe to be used in the enclosed environment of a crewed space vehicle; and safe to be mounted or used in unpressurized spaces adjacent to habitable areas.

Battery design review, approval, and certification is required before the batteries can be used for ground operations and be certified for flight.

ACKNOWLEDGMENT

The authors would like to acknowledge the significant contributions of Dr. Chris Iannello (NESC Technical Fellow for Electrical Power), Paul Shack (NESC-SEI), Robert Button (NESC-Discipline Deputy Power), Dr. Daniel Doughty (NESC-Battery Specialist), Concha Reid (NASA-GRC-Battery Specialist), Jeffrey Brewer (NASA-MSFC-Battery Specialist), Thomas Miller (NASA-GRC-Battery Specialist), Margaret McPhail (JSC-S&MA), Trent Kite (JSC-S&MA), Dr. Bugga Ratnakumar (JPL-Battery Specialist), Penni Dalton (NASA-GRC-Battery Specialist), and Jonay Campbell (NESC TDT support).

Revised by: SAMUEL RUSSELLDigitally signed by SAMUEL RUSSELL
DN: c=US, o=U.S. Government, ou=NASA, ou=People,
cn=SAMUEL RUSSELL, 0.9.2342.19200300.100.1.1=srussell
Date: 2017.03.09 13:01:54 -06'00'Samuel Russell
Power Systems Branch, EP5

Date

Reviewed by: DAVID DELAFUENTEDigitally signed by DAVID DELAFUENTE
Date: 2017.03.09 13:22:14 -06'00'David Delafuente
Battery Safety Technical Discipline Lead
Power Systems Branch, EP5

Date

ERIC DIMPAULT-DARCY
2017.03.09 14:35:55 -06'00'Eric Darcy
Battery Systems Technical Discipline Lead
Power Systems Branch, EP5

Date

Approved by: KARLA BRADLEYDigitally signed by KARLA BRADLEY
DN: c=US, o=U.S. Government, ou=NASA, ou=People,
cn=KARLA BRADLEY, 0.9.2342.19200300.100.1.1=kfbradle
Date: 2017.03.09 15:49:51 -06'00'Karla Bradley
Chief
Power Systems Branch, EP5

Date

EDGAR CASTRODigitally signed by EDGAR CASTRO
DN: c=US, o=U.S. Government, ou=NASA, ou=People,
cn=EDGAR CASTRO, 0.9.2342.19200300.100.1.1=ecastro
Date: 2017.03.20 14:13:13 -05'00'Edgar O. Castro
Chief
Propulsion and Power Division, EP

Date

MARY SCHWARTZDigitally signed by MARY SCHWARTZ
DN: c=US, o=U.S. Government, ou=NASA, ou=People,
cn=MARY SCHWARTZ, 0.9.2342.19200300.100.1.1=mbschwar
Date: 2017.03.30 13:00:13 -05'00'Lauri Hansen
Director
Engineering Directorate

Date

Change Record

Rev.	Date	Originator	Description
Basic	September 1985	Bobby Bragg	Original version
A	January 2005	Judith Jeevarajan Eric Darcy	Revised to update battery chemistries, hazards, and controls. Changed from a handbook/guideline to a requirements document.
B	April 2006	Judith Jeevarajan	Revised to clarify sentences and requirements for each chemistry; added new section for vibration requirements.
C	January 2014	Judith Jeevarajan, Eric Darcy, with support from other members of the Agency Power Technical Discipline Team	Revised to clarify all requirements, specifically, lithium-ion battery chemistry; added new sections for lithium-sulfur and thermal battery chemistries, as well as supercapacitors. Significant reformat to aid in readability and identification of requirements vs. best practice. Added thermal runaway propagation evaluation, as well as other lessons learned from lithium-ion battery incidents of 2013.

D	March 8, 2017 EA CCB CR/D EA-0229	Samuel Russell	Included risk characterization methodology and consolidated non-critical criteria, increased non-critical threshold from 300 to 1000mAh, removed vacuum leak checks for non-critical chemistries, defined cell DPA quantity, updated internal references to Appendix A, incorporated alkaline shelf life memo (EP-11-042), and incorporated recommended changes from ISS CR 014210 basic and revision A: updated applicable and reference document tables, removed references to Form 1230 and Form 1298, corrected qualification test vacuum pressure limit, clarified lot testing requirements, extended vendor configuration control authority to International Partners, added computer based control requirements and verification references, clarified toxicology assessment description, removed legacy voltage limit on electrical short requirement, included functional test definition, added Unique Hazard Report requirement, clarified transport requirements for lithium sulfur cells, updated safety review requirement, certification and training, and shipping references.
---	--	----------------	--

Table of Contents

PREFACE	II
ACKNOWLEDGMENT	II
CHANGE RECORD	IV
TABLE OF CONTENTS	VI
1. INTRODUCTION	1
1.1 PURPOSE AND SCOPE	1
1.2 RESPONSIBILITY AND CHANGE AUTHORITY	2
1.3 BATTERY DESIGN EVALUATION AND APPROVAL	2
2. APPLICABLE DOCUMENTS.....	3
2.1 APPLICABLE DOCUMENTS.....	3
2.2 REFERENCE DOCUMENTS.....	4
2.3 ORDER OF PRECEDENCE.....	6
3. ACRONYMS AND DEFINITIONS	7
3.1 ACRONYMS AND ABBREVIATIONS	7
3.2 DEFINITIONS	8
4. GENERAL BATTERY REQUIREMENTS	13
4.1 METHODOLOGIES USED IN ENSURING SAFE OUTCOMES.....	13
4.1.1 FAILURE TOLERANCE.....	13
4.1.2 DESIGN FOR MINIMUM RISK (DFMR).....	13
4.1.3 RISK CLASSIFICATION	14
4.2 KEY ASPECTS OF ENGINEERING EVALUATION, QUALIFICATION, AND ACCEPTANCE TESTING	16
4.2.1 ENGINEERING EVALUATION	16
4.2.2 QUALIFICATION TESTING.....	18
4.2.3 ACCEPTANCE TESTING	19
4.3 MANUFACTURING QUALITY	20
4.3.1 CONFIGURATION CONTROL	20
4.3.2 SUBSEQUENT FLIGHT LOT TESTING.....	21
4.4 GENERAL DESIGN REQUIREMENTS	22
4.4.1 ELECTRICAL INTERCONNECTION.....	23
4.4.2 ELECTRICAL WIRING.....	23
4.4.3 LITHIUM-ION BATTERY AND CELL MONITORING.....	23
4.4.4 CELL MATCHING.....	24
4.4.5 DISSIMILAR CONTROLS	24
4.5 MISSION USAGE.....	25
4.6 POST-FLIGHT CELL AND PACK EVALUATION.....	26
4.7 GROUND PROCESSING REQUIREMENTS	26
4.7.1 REQUIREMENTS FOR GROUND HANDLING AND TRANSPORTATION	26
4.7.2 DESIGN AND OPERATIONS REQUIREMENTS FOR GROUND SUPPORT EQUIPMENT	28
4.8 SHELF AND SERVICE LIFE RELATED REQUIREMENTS	29
5. GENERAL BATTERY HAZARDS AND CONTROLS	30
5.1 FIRE/EXPLOSION HAZARD	30
5.1.1 SOURCES – CHEMICAL REACTION	30
5.1.2 SOURCES – OVERCHARGE FAILURE/OVER-DISCHARGE FAILURE.....	33
5.1.3 SOURCES – EXTERNAL SHORT CIRCUIT.....	35
5.1.4 SOURCES – INTERNAL SHORT CIRCUIT FAILURE	39
5.1.5 SOURCES – THERMAL RUNAWAY PROPAGATION	43

5.2	CHEMICAL EXPOSURE HAZARDS	45
5.2.1	CHEMICAL EXPOSURE SOURCES – MECHANICAL FAILURE	45
5.2.2	SOURCES – SEALS AND VENTS	47
5.3	ELECTRICAL HAZARDS	48
5.3.1	SOURCES OF ELECTRICAL SHOCK, CORONA, AND ARC-FLASH.....	48
5.3.2	SOURCES OF LOSS OF POWER.....	48
5.4	EXTREME TEMPERATURE HAZARDS	50
5.4.1	SOURCES	50
5.4.2	REQUIREMENTS	50
6.	SAFETY RELEVANT TO SPECIFIC BATTERY CHEMISTRIES.....	53
6.1	ALKALINE PRIMARY BATTERIES.....	55
6.1.1	DEFINITION	55
6.1.2	HAZARD SOURCES	56
6.1.3	CONTROLS/PROCESS REQUIREMENTS	56
6.2	ALKALINE SECONDARY BATTERIES.....	56
6.2.1	DEFINITION	56
6.2.2	HAZARD SOURCES	57
6.2.3	CONTROLS/PROCESS REQUIREMENTS	57
6.3	LEAD-ACID BATTERIES	57
6.3.1	DEFINITION	57
6.3.2	HAZARD SOURCES	58
6.3.3	CONTROLS/PROCESS REQUIREMENTS	58
6.4	LITHIUM-ION SECONDARY BATTERIES.....	58
6.4.1	DEFINITION	58
6.4.2	HAZARD SOURCES	61
6.4.3	CONTROLS/PROCESS REQUIREMENTS	62
6.5	LITHIUM/LITHIUM-ION POLYMER SECONDARY BATTERIES	69
6.5.1	DEFINITION	69
6.5.2	HAZARD SOURCES	71
6.5.3	CONTROLS/PROCESS REQUIREMENTS	71
6.6	LITHIUM PRIMARY BATTERIES	73
6.6.1	DEFINITION	73
6.6.2	HAZARD SOURCES	74
6.6.3	CONTROLS/PROCESS REQUIREMENTS	75
6.6.4	CERTIFICATION REQUIREMENT FOR HANDLING LITHIUM BATTERIES	78
6.6.5	APPLICATION OF UL DATA	78
6.6.6	PREPACKAGED MULTI-CELLED BATTERIES	78
6.7	NICKEL-CADMIUM BATTERIES	78
6.7.1	DEFINITION	78
6.7.2	HAZARDS	79
6.7.3	CONTROLS/PROCESS REQUIREMENTS	79
6.8	NICKEL-HYDROGEN BATTERIES	80
6.8.1	DEFINITION	80
6.8.2	HAZARD SOURCES	80
6.8.3	CONTROLS/PROCESS REQUIREMENTS	80
6.9	NICKEL-METAL HYDRIDE BATTERIES.....	81
6.9.1	DEFINITION	81
6.9.2	HAZARDS	82
6.9.3	CONTROLS/PROCESS REQUIREMENTS	82
6.10.1	DEFINITION	83
6.10.2	HAZARD SOURCES	84
6.10.3	CONTROLS/PROCESS REQUIREMENTS	84
6.11	ZINC-AIR BATTERIES	86

6.11.1	DEFINITION	86
6.11.2	HAZARD SOURCES	86
6.11.3	CONTROLS/PROCESS REQUIREMENTS	86
6.12	LITHIUM-SULFUR.....	87
6.12.1	DEFINITION	87
6.12.2	HAZARDS	88
6.12.3	CONTROLS.....	88
6.13	THERMAL BATTERIES.....	89
6.13.1	DEFINITION	89
6.13.2	HAZARDS	89
6.13.3	CONTROLS.....	89
6.14	CAPACITORS/SUPERCAPACITORS.....	90
7.	REFERENCES	91
8.	APPENDICES.....	92

List of Figures

FIGURE 6.4.3-1.	CELL ACCEPTANCE FLOW WITH LARGE NUMBERS OF SMALLER, HIGH-VOLUME COMMERCIAL CELLS.....	66
FIGURE 6.4.3-2.	CELL ACCEPTANCE FLOW WITH SMALL NUMBERS OF LARGER, LOWER VOLUME CUSTOM CELLS.....	67
FIGURE 6.4.3-3.	COTS BATTERY ACCEPTANCE FLOW	69
FIGURE 6.6.3-1.	FUSE AND DIODE PROTECTION OF A CELL	76
FIGURE 6.6.3-2.	REDUNDANT PARALLEL BLOCKING DIODES FOR EACH SERIES STRING IN A PARALLEL-SERIES BATTERY COMBINATION.....	77

List of Tables

TABLE 6.6.2-1.	ENERGY DENSITY OF DIFFERENT CELL CHEMISTRIES (MANUFACTURER'S DATA)	74
----------------	--	----

List of Appendices

APPENDIX A:	QUALIFICATION AND FLIGHT ACCEPTANCE VIBRATION TESTING FOR BATTERIES	93
APPENDIX B:	CUSTOM CELL MANUFACTURING FACILITY AUDITS.....	99
APPENDIX C:	SHELF AND SERVICE LIFE FOR VARIOUS CELL/BATTERY CHEMISTRIES	102
APPENDIX D:	BATTERY DESIGN EVALUATION AND APPROVAL.....	104
APPENDIX E:	REQUIREMENTS MATRIX.....	105

CREWED SPACE VEHICLE BATTERY SAFETY REQUIREMENTS

1. INTRODUCTION

1.1 Purpose and Scope

This requirements document is applicable to all batteries on crewed spacecraft, including vehicle, payload, and crew equipment batteries. It defines the specific provisions required to design a battery that is safe for ground personnel and crew members to handle and/or operate during all applicable phases of crewed missions, safe for use in the enclosed environment of a crewed space vehicle, and safe for use in launch vehicles, as well as in unpressurized spaces adjacent to the habitable portion of a space vehicle. The required provisions encompass hazard controls, design evaluation, and verification. The extent of the hazard controls and verification required depends on the applicability and credibility of the hazard to the specific battery design and applicable missions under review. Evaluation of the design and verification program results shall be completed prior to certification for flight and ground operations.

This requirements document is geared toward the designers of battery systems to be used in crewed vehicles, crew equipment, crew suits, or batteries to be used in crewed vehicle systems and payloads (or experiments). This requirements document also applies to ground handling and testing of flight batteries. Specific design and verification requirements for a battery are dependent upon the battery chemistry, capacity, complexity, charging, environment, and application. The variety of battery chemistries available, combined with the variety of battery-powered applications, results in each battery application having specific, unique requirements pertinent to the specific battery application. However, there are basic requirements for all battery designs and applications, which are listed in section 4. Section 5 includes a description of hazards and controls and also includes requirements.

The following definitions differentiate between requirements and other statements.

- Shall: This is the only verb used for binding requirements.
- Should/May: These verbs are used for stating non-mandatory goals or when used in the italicized text herein refer to best practice methods which can be construed as example methods for meeting the requirement it refers to.
- Will: This verb is used for stating facts or declaration of purpose.

Section 6 includes chemistry-specific information. No requirements appear in that section, only best practices.

Shall requirements are summarized in Appendix E.

In keeping with the NASA standards template, italicized text is intended to indicate rationale, best practice examples, or guidelines; while the italicized text never includes the requirement, it often helps to convey the intent of the requirement.

In cases where a requirement includes associated italicized text and that text includes best practice, that best practice can be considered part of an accepted means to address the requirement. If other methods are used, rationale and supporting data demonstrating the adequacy of those methods should be presented and must be reviewed for adequacy by the program's technical team.

1.2 Responsibility and Change Authority

The responsibility for the development of this document lies with the Propulsion and Power Division at NASA Johnson Space Center (JSC). Change authority resides with the Propulsion and Power Division.

1.3 Battery Design Evaluation and Approval

To be compliant to the requirements herein, every battery design, along with its safety verification program, its ground and/or on-orbit usage plans, and its post-flight processing shall be evaluated and approved by the appropriate technical review panel in the given program or project. Center and program specific examples of the review and approval process can be found in Appendix D.

2. APPLICABLE DOCUMENTS

2.1 Applicable Documents

Document Number	Document Title
JPR 1700.1	JSC Safety and Health Handbook
JSC-STD- 8080	JSC Design and Procedural Standards
JSC 25159	Toxicological Hazard Assessments on Batteries used in Space Shuttle Missions
JSC 66548	Requirements for Flight Certification and Acceptance of Commercial Off the Shelf Lithium Ion Batteries
JSC 26895	Guidelines for Assessing the Toxic Hazard of Spacecraft Chemicals and Test Materials
49 CFR 173.185	Transportation Requirements for Lithium Cells and Batteries
JWI 8705.3	Battery Processing
SSP 52005 Rev. C	Payload Flight Equipment Requirements and Guidelines for Safety-Critical Structures
SSP 50021	Safety Requirements for ISS Program
SSP 41172	Qualification and Acceptance Environmental Test Requirements for Space Station
SSP 51700	Payload Safety Policy and Requirements for the International Space Station (ISS)
SSP 30599	Safety Review Process International Space Station
SSP 50038	Computer Based Control System Safety Requirements
NASA-STD-5019	Fracture Control Requirements for Spaceflight Hardware
NASA-STD-3001	NASA Space Flight Human-System Standard
ANSI/AIAA S-080-1998	Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
NPR 8705.2B	Human-Rating Requirements for Space Systems
NSTS 1700.7B ISS Addendum	Safety Policy and Requirements for Payloads Using the International Space Station
AWS C7.4/C7.4M:2008	Process Specification and Operator Qualification for Laser Beam Welding
NASA-STD-5020	Requirements for Threaded Fastening Systems in Spaceflight Hardware
PRC-0009D	Resistance Spot Welding of Battery and Electronic Assemblies
UL 840	Insulation Coordination Including Clearances and Creepage Distances for Electrical Equipment
NASA-STD-8739.4	Crimping, Interconnecting Cables, Harnesses, and Wiring

J-STD-001ES	Space Applications Electronic Hardware Addendum to J-STD-001E
NASA-STD-8739.1A	Workmanship Standard for Polymeric Application on Electronic Assemblies
MIL-STD-1686	Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies and Equipment
IPC-6012C-2010	Qualification and Performance Specification for Rigid Printed Boards

2.2 Reference Documents

This section lists those documents that may aid in the understanding or clarification of the specification.

Document Number	Document Title
NPR 8705.4	Risk Classification for NASA Payloads
JSC 26626A	EVA Hardware Generic Design Requirements
JSC 26549	JSC Manual for Control of Program Stock
JSC 26943	Guidelines for the Preparation of Payload Flight Safety Data Packages and Hazard Reports
JSC 61360	Engineering Directorate Certified Parts Approval Process (EDCPAP)
EP-WI-031	Specification for Acceptance Testing of Commercial Lithium Ion Cell Lots
SMC-S-016	Test Requirements for Launch, Upper Stage and Space Vehicles
JSC 66217	Specification for Lot Testing and Flight Screening of Canon BP 927 and BP 930 Lithium-ion Batteries
EP-WI-014 Rev. B	Specification for Acceptance Testing of Commercial Nickel Metal Hydride (NiMH) and Nickel Cadmium (NiCd) Cells
ISS_EP -03	EP5 Battery Design Evaluation Form
Form 1298	Flight Payload Standardized Hazard Control Report
ESTA-OP-049 Ver. D	Lithium Battery Handler Certification
P32928-103	Requirements For International Partner Cargoes Transported on Russian Progress and Soyuz Vehicles
JSC 50835A	ISS Pressurized Volume Hardware Common Interface Requirements Document
NESC-RP-08-00492	Assessment of Risks and Mitigation Strategies for the use of Lithium-ion (Li-ion) Long Life Batteries (LLB)
MSFC-STD-531	High Voltage Design Guide
JSC 29129	STS Orbiter Upgrades Program – Electrical Auxiliary Power Unit (EAPU) Corona Design Guideline

SSP 30309	Safety Analysis and Risk Assessment Requirements Document
CCT-STD-1140	Crew Transportation Technical Standards and Design Evaluation Criteria
CCT-REQ-1130	ISS Crew Transportation and Services Requirements Document

2.3 Order of Precedence

This is a safety requirements document. Wherever there is conflict between this and reference documents, the following hierarchy applies:

1. Program-level documentation/specifications (International Space Station (ISS), Commercial Crew, etc.)
2. JSC Engineering Directorate documentation/specifications
3. This document
4. Any other document/specification cited herein

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

A	amperes (current)
AC	Alternating Current
Ag/Zn	Silver-zinc
AgO	Silver (II) oxide
Ag ₂ O	silver (I) oxide or monovalent silver oxide
Ah	ampere-hour
ARC	Accelerating Rate Calorimetry
AVT	Acceptance Vibration Test
°C	degrees Centigrade
CCV	Closed Circuit Voltage
Cd(OH) ₂	Cadmium hydroxide
CFE	Contractor Furnished Equipment
CID	Current Interrupt Device
COTS	Commercial Off the Shelf
C rate or C	Charge/discharge rate based on the nameplate capacity of the cell
CT	Computed Tomography
DC	Direct Current
DFMR	Design for Minimum Risk
DoD	Depth of Discharge
DOT	Department of Transportation
DPA	Destructive Physical Analysis
ESTA	Energy Systems Test Area
°F	degrees Fahrenheit
G	Gravitational Constant
g ² /Hz	Measurement of Vibration Amplitude
GEO	Geosynchronous Earth Orbit
GFE	Government Furnished Equipment
GSE	Ground Support Equipment
HAZMAT	Hazardous Material
ISRP	ISS Safety Review Panel
ISS	International Space Station
JF	JSC Form
JSC	Johnson Space Center
KOH	Potassium hydroxide
LEL	Lower Exposure Limit
LEO	Low Earth Orbit
Li-BCX	Lithium-bromine chloride complex
LiBOB	Lithium bisoxalato borate
LiBF ₄	Lithium tetrafluoroborate
LiCF _x	Lithium polycarbon monofluoride

LiFeS ₂	Lithium iron disulfide
Li-MnO ₂	Lithium manganese dioxide
LiPF ₆	Lithium hexafluorophosphate
Li-SO ₂	Lithium-sulfur dioxide
Li-SO ₂ Cl ₂	Lithium-sulfuryl chloride
Li-SOCl ₂	Lithium-thionyl chloride
Li-ion	Lithium-ion
mAh	milliamp-hours
MCMB	Mesophase Carbon Micro Beads
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NDE	Nondestructive Evaluation
NiCd	Nickel-cadmium
NiH ₂	Nickel-hydrogen
NiMH	Nickel-metal hydride
NiOOH	Nickel oxyhydroxide
NPR	NASA Procedural Requirement
NSTS	National Space Transportation System
OCV	Open Circuit Voltage
OEM	Original Equipment Manufacturer
PAN	Polyacrylonitriles
PbO ₂	Lead dioxide
PSRP	Payload Safety Review Panel
PTC	Positive Temperature Coefficient
PVC	Polyvinyl chloride
PVDF	Polyvinylidene Di-fluoride
QVT	Qualification Vibration Testing
SDS	Safety Data Sheet
SLA	Sealed Lead Acid
SO ₂	Sulfur dioxide
SOC	State of Charge
STS	Space Transportation System (Space Shuttle)
UL	Underwriters Laboratory
V	Voltage, in volts
VRLA	Vent Regulated Lead Acid
Wh	watt-hour

3.2 Definitions

Activation: The process of making an assembled cell functional, either by introducing an electrolyte, by immersing the cell into an electrolyte, or by any other means dictated by the cell manufacturer.

Active material: The material contained in the electrodes of a cell or battery that takes part in the electrochemical reactions of charge and discharge.

Aging: Permanent loss of capacity due to repeated cycling or passage of time during nonuse.

Anode – (negative electrode): Gives up electrons to external circuit and is oxidized during the electrochemical reaction of discharge.

Available capacity: The total capacity, ampere-hour (Ah) or watt-hour (Wh), that will be obtained from a cell or battery at defined discharge rates and other specified discharge or operating conditions (including temperatures).

Battery (also termed battery pack): Interconnected modules, including all ancillary subsystems for mechanical support, thermal management, and electronic control.

C rate: The discharge or charge current, in amperes, expressed as a multiple of the rated capacity in ampere hours.

Capacity: The total number of ampere-hours or watt-hours that can be withdrawn from a fully charged cell or battery under specified conditions of discharge.

Catastrophic failure mode: An event that results in the death or permanent disability of a crew member or passenger, or an event results in the unplanned loss/destruction of a major element of the crewed space system that could potentially result in the death or permanent disability of a crew member or passenger.

Cathode – (positive electrode): Accepts electrons from the circuit and is reduced during the electrochemical reaction of discharge.

Cell (also termed battery cell): An assembly of at least one positive electrode, one negative electrode, and other necessary electrochemical and structural components. A cell is a self-contained energy storage device whose function is to deliver electrical energy to an external circuit.

Cell bank: A grouping of interconnected cells in a parallel arrangement, into a single mechanical and electrical unit.

Certification: The result of the qualification and design review process, often documented by memorandum or completion of requirement verification list, table, or document specific to the end item being certified.

Charge acceptance: The willingness of a battery or cell to accept charge. It may be affected by cell temperature, charge rate, and state of charge (SOC).

Closed circuit voltage (CCV): The difference in potential between the terminals of a cell or the voltage measured when the circuit is under an electrical load.

Concentration polarization: Polarization caused by the depletion of ions in the electrolyte at the surface of the electrode.

Conditioning: Cyclic charging and discharging of a battery to ensure that it is fully formed and fully charged. Also carried out when a battery is first placed into service or returned to service after prolonged storage. In some cases, this may involve deep discharging as in the case of NiCd or NiMH.

Cutoff voltage: The cell or battery voltage at which the discharge is terminated. Also called end voltage.

COTS battery: Original equipment manufacturer (OEM) battery designed to power commercially available (or COTS) equipment. Examples include cameras, laptops, tablets, power tools, etc.

Custom battery: Any battery designed for the purpose of powering non-COTS applications. It is designed with either COTS or custom cells.

Cycle testing: Repetitive charge discharge tests performed to demonstrate rate performance capability or verify continued operability after completing acceptance testing.

Depth of discharge (DOD): Ratio of the quantity of electricity (in amp-hours or watt-hours) removed from a cell or battery on discharge to its rated capacity.

Electroformation: Term used to describe the conversion of the material in both the positive and negative plates to their respective active materials. Also called 'formation'.

End voltage: The prescribed voltage at which the discharge (or charge, if the end-of-charge voltage) of a cell or battery should be terminated per the application or the manufacturer's specification/recommendation.

Fast charge: A rate of charging that returns full capacity to a rechargeable battery, at a rate higher than the nominal rate recommended by the cell/battery manufacturer.

Flooded cell: A cell design that incorporates an excess amount of electrolyte.

Forced discharge: Discharging a cell or battery below zero volts causing voltage reversal.

Formation: Electrochemical processing of a battery plate or electrode that transforms the active materials into usable form. Also referred to as 'electroformation'.

Gassing: The evolution of gas from one or more of the electrodes or the electrolyte in a cell.

Internal resistance: The opposition to the flow of electric current within a cell or battery expressed as the sum of the ionic and electronic resistances of the cell components.

Life: For rechargeable batteries, the duration of satisfactory performance, measured in years (calendar or shelf life) or in the number of charge/discharge cycles (cycle or service life). For primary batteries, the duration of satisfactory performance measured in years (calendar or shelf life) or the period of performance under load (service life).

Memory effect: A phenomenon in which a cell, operated in successive cycles to less than full DoD, experiences a depression of its discharge voltage and temporary loss of the rest of its capacity when cycled again at normal voltage levels.

Module: A grouping of interconnected cells in series and/or parallel arrangement into a single mechanical and electrical unit.

Open circuit voltage (OCV): The difference in potential between the terminals of a cell or the voltage measured when the circuit is open (no-load condition).

Overcharge: The forcing of current through a cell after all of the active material has been converted to the charged state. Charging continued after 100-percent SOC is achieved.

Over-discharge: To discharge a cell or battery past the point where the full capacity has been obtained.

Nominal voltage: The reported or reference voltage of the cell/battery, also sometimes referred to as the “normal” voltage of the cell/battery.

Oxygen recombination: The process by which oxygen generated at the positive plate during charge is reacted at the negative plate.

Prismatic cells: A cell fabricated typically with flat plate electrodes, which are stacked to provide capacity.

Rated capacity: The number of ampere-hours a cell or battery can deliver under specific conditions (rate of discharge, end voltage, temperature), usually, the manufacturer’s rating.

Shape change: Change in shape of an electrode due to migration of active material during charge/discharge cycling.

Shelf life: The duration of storage under specified conditions at the end of which a cell or battery still retains the ability to give a specified performance.

Starved electrolyte cell: A cell containing little or no free liquid electrolyte.

State of charge (SOC): The available charge capacity in a cell or battery expressed as a percentage of rated capacity.

Taper charge: A charge regime delivering moderate- to high-rate charge current when the battery is at a low SOC and tapering the charge current to lower values as the battery reaches its end-of-charge voltage.

Thermal runaway: A condition whereby a cell or battery overheats and reaches very high temperatures in very short periods (i.e., seconds) through internal heat generation caused by an internal short or due to an abusive condition. The temperature of the cell or battery is uncontrollable at this point.

Trickle charge: A charge at a low rate, balancing losses through a local action and/or periodic discharge, to maintain a cell or battery in a fully charged condition.

Unactivated shelf life: The period of time, under specified conditions of temperature and environment, that an unactivated cell or battery can be stored before deteriorating below a specified capacity.

Wet shelf life: The period of time that a cell or battery can stand in the charged or activated condition before deteriorating below a specified capacity.

Working voltage: The typical voltage or range of voltage of a cell or battery during discharge.

4. GENERAL BATTERY REQUIREMENTS

The following sections address general technical requirements intended to ensure safe outcomes in NASA battery deployments, addressing issues related to design, manufacture, qualification, and acceptance.

4.1 Methodologies used in Ensuring Safe Outcomes

A key aspect of ensuring safe outcomes is the approach taken to control hazards. The following section addresses the prescribed strategies: failure tolerance and Design for Minimum Risk (DFMR).

4.1.1 Failure Tolerance

Failure tolerance is the basis of the NASA safety approach. This method is applied in all safety evaluations unless it can be proven that a failure tolerance approach is not feasible.

- a. Battery systems for crewed spacecraft shall implement failure tolerance as the preferred approach to control all catastrophic hazard causes.
- b. The level of failure tolerance shall be the product of an integrated design and safety analysis but be a minimum of one.

As an example, to be considered two-fault tolerant, a battery design should be capable of maintaining safe operation or incur a safe shutdown after the imposition of the failure of any two mutually independent catastrophic hazard control measures or features.

For the purposes of fault tolerance discussions, NASA Procedural Requirements (NPR) 8705.2B, "Human Rating Requirements and Guidelines for Space Flight Systems," defines "catastrophic event" as one resulting in the death or permanent disability of a crew member or passenger or an event resulting in the unplanned loss/destruction of a major element of the crewed space system during the mission that could potentially result in the death or permanent disability of a crew member or passenger.

Fault tolerance for batteries should consider the toxicity as well as the energy content. This takes into consideration the causes resulting in leakage, rupture, electrical shock, fire, and explosion hazards.

Note that SSP 30309 provides the requirements for the safety analysis and risk assessment for the ISS.

4.1.2 Design for Minimum Risk (DFMR)

Some potentially catastrophic hazards cannot practically be controlled using failure tolerance and are exempted from the tolerance requirement provided the risk they pose is mitigated to the maximum practical extent through a defined process in which

approved standards and margins are implemented to account for the absence of failure tolerance. Herein, this process is called DFMR.

- a. The DFMR approach shall be used to address catastrophic battery hazards that cannot practically be controlled by a failure tolerance approach.

NPR 8705.2B, "Human Rating Requirements and Guidelines for Space Flight Systems," recognizes that some potentially catastrophic hazards cannot be practically controlled using failure tolerance and are exempted from the tolerance requirement provided they are controlled through a defined process in which approved standards and margins are implemented to account for the absence of failure tolerance. Herein, this process is called DFMR.

DFMR is a process that relies on the application of mature/proven technology, robust design margins, and accepted standards for manufacturing, inspection, analysis, test, and operational measures to mitigate the potential for failures that cannot be controlled by failure tolerance. When a DFMR approach is used, technical authorities accept that the process has demonstrated the risk of catastrophic hazards has been minimized to the maximum practical extent.

A risk matrix may be used to demonstrate that the applied methods have reduced the probability of occurrence and/or the severity of the hazards to an acceptable level for the intended use.

This approach to hazard control takes advantage of existing acceptable processes and best practices. Guidance and recommendations for acceptable processes and best practices are given in Sections 5.0 and 6.0 and in the appendices. If other methods are used, rationale and supporting data demonstrating the adequacy of those methods should be presented.

Examples of the kinds of battery failures that might employ DFMR include leakage and internal short. Many battery or cell designs become impractical with the implementation of triple containment to be two-fault tolerant to catastrophic electrolyte leakage. Similarly, the imposition of three layers of separators between anode and cathode to be two-fault tolerant to catastrophic cell internal short circuits hazards in many cases can severely degrade performance.

For the purposes of streamlining the battery design approval, some simple battery designs below certain low energy and voltage thresholds as specified in Sections 4, 5 and 6 herein also can use the DFMR approach for hazard control.

4.1.3 Risk Classification

Three levels of risk classifications have been defined for battery systems included in this specification. Threshold limits are defined based on contained energy and experience with specific manufacturing methods and cell formats. Safety of crew, vehicle, and mission may be a factor in selecting the appropriate classification. For systems which do not confirm with established limits, the next higher level of classification is

recommended. Threshold limits are defined for each chemistry in Section 6 of this document. Risk classes are defined as:

- Non-Critical – the lowest level of hazard control is reserved for low energy cells and battery designs for which standard emergency procedures are written and practiced. Batteries within this ‘Non-Critical’* classification shall be:
 - o Low energy < 4 Wh per battery pack where each battery is thermally and electrically isolated (or < 60Wh for Alkaline Primary Batteries) where Watt-Hours (Wh) = Cell Capacity (Ah) × Cell Voltage (V), and
 - o Rated with a toxicological level of 1 or 2, and
 - o Contained within a not intentionally sealed compartment, and
 - o Meet one the following criteria for its chemistry:
 - Alkaline Primary Batteries - Alkaline (non-rechargeable) cells in sizes D or smaller with a maximum of 12 V and/or 60 Wh and with cells either all in series or all in parallel and with no potential charging source and with the cells located in a vented compartment. Silver oxide cells are considered within this category.
 - Lithium-ion Secondary Batteries – COTS (rechargeable) lithium-ion button, cylindrical, or pouch batteries of up to 1000 mAh capacity. Battery is defined as one cell or a packaged or unpackaged assembly of two or more cells.
 - Lithium Primary Batteries - COTS (non-rechargeable) lithium button cells (only Li-MnO₂, Li-CFx and LiFeS₂) of up to 1000 mAh capacity.
 - Nickel Cadmium Batteries - Nickel-cadmium (rechargeable) batteries and cells of up to 1000 mAh capacity.
 - Nickel-Metal Hydride Batteries - Nickel-metal hydride (rechargeable) silver ox batteries and cells of up to 1000 mAh capacity.
 - Silver-Zinc Batteries - Silver-zinc (rechargeable) batteries and cells of up to 1000 mAh capacity.
 - Zinc-Air Primary Batteries - Zinc-air (non-rechargeable) batteries and cells of up to 1000 mAh capacity.
 - *Note: For primary cells, rated cell capacity is defined as the maximum stated capacity per cell product data sheet*
- Critical – the intermediate level of risk classification requiring single fault tolerance typical of commercial devices manufactured in high volumes for the global consumer. Batteries within this ‘Critical’* classification shall be one of these chemistries and do not meet the ‘Non-Critical’ classification:
 - o Lithium Ion Secondary Batteries – COTS (rechargeable) lithium ion of less than 20 V and 60 Wh
 - o Nickel Cadmium
 - o Nickel Metal Hydride
 - o Silver Zinc
 - o Alkaline Primary

- o Lithium Primary
- o Zinc-Air
- Catastrophic – the highest level of risk classification requiring two fault tolerance typical of custom, high energy, or high power designs.

** Note: The term “non-critical” described within this section differs in context and is not to be confused with the ISRP hazard severity definitions of “critical hazards” as defined within SSP 30599, SSP 50021, and SSP 51700.*

4.2 Key Aspects of Engineering Evaluation, Qualification, and Acceptance Testing

The thorough nature of NASA’s test regime from early engineering evaluation, through qualification, and ultimately to acceptance testing is a key aspect in the Agency’s safe use of batteries in its missions. The following section specifies general requirements in those areas and provides references to additional best practices.

Application of the requirements in this section is dependent on risk classification. The italicized text provides guidance for requirement application to critical and non-critical battery systems.

JSC 66548 can be used as an example for the flight certification and acceptance of COTS lithium-ion batteries that details the level of testing required under the engineering, qualification, flight acceptance, and lot sample testing of COTS lithium-ion batteries.

4.2.1 Engineering Evaluation

This section addresses the preliminary evaluation of safety and performance features at both the cell and battery level and would include the evaluation testing of prospective cells before their selection for use in a flight battery. Engineering evaluation commonly includes abuse test protocols intended to assess safety and performance features necessary for the battery design.

- a. Cell and battery designs considered for flight shall first undergo evaluation testing to characterize the performance and safety of the flight battery design.
- b. Evaluation testing shall, at a minimum, consist of characterizing the cell and battery safety under abuse conditions of overcharge, over-discharge into reversal, external short circuit and cell internal short circuit, temperature tolerance, vent and burst pressure determination and for critical/catastrophic batteries (See 4.1.3) perform cell destructive physical analysis.
- c. Evaluation testing shall confirm manufacturer’s specifications that are relevant to the project, as well as confirm that the cell and/or battery design can handle unique requirements levied by the project.

In the case where safety features at the cell level are rendered less effective when the cells are assembled into the battery, abuse testing at the cell level and then subsequently at progressive levels of assembly evaluates the effectiveness of these features.

Establish a baseline characterization of thermal signature (calorific output as a function of temperature) for cells being used in custom batteries. Accelerating Rate Calorimetry (ARC) is one such method.

Cell designs used in custom batteries should be examined by a combination of computed tomography and destructive physical analysis (DPA) (tear down) to assess quality of manufacture and absence of defects.

When performing battery safety tests that simulate abuse conditions, the mechanical and thermal environment of the test article should be representative of conditions expected during normal use.

4.2.2 Qualification Testing

This section addresses the qualification testing of the flight battery.

- a. Qualification testing shall be performed to the worst-case relevant flight environments with margin.

The qualification sample of batteries should be randomly sampled from units from the flight lot that have passed acceptance testing.

- b. Environmental tests shall include, at a minimum, extreme temperature exposures, vacuum, and vibration tests.

The margin used for qualification tests will be provided by the respective projects or programs or from SSP41172 for ISS environments. Appendix A may be used as a guideline for qualification vibration tests (QVTs) for cells and batteries if there are no project-provided environments. The margin proposed here should be consistent with the program's margining policies. In the event none are provided, as a guideline, 6 db above the maximum expected is typically used.

The qualification of the battery should include testing the batteries to environmental and vibration levels that are higher than the mission requirements. The number of flight missions that the batteries will be used for, along with the location of the battery in the spacecraft, should determine the period and level of vibration. As a minimum, the qualification test program should include the following:

1. *Functional baseline test (open circuit voltage (OCV), mass, capacity or load check, internal resistance, visual inspection).*
2. *Vibration to qualification levels.*
3. *Functional baseline test recheck.*
4. *Charge/discharge cycles (for rechargeable batteries) or a load test (for primary batteries) at 20 degrees Fahrenheit (°F) margin above and below worst-case hot and worst-case cold, respectively.*
5. *Functional baseline test recheck.*
6. *Vacuum (approx. 0.1 psi) or equivalent leak checks.*
7. *Functional baseline test recheck.*

For batteries used in a pressurized volume or environment, exposure to a vacuum environment (approximately 0.1 psi) for a minimum of 6 hours should be carried out. For batteries used in an unpressurized volume or environment, thermal vacuum cycles must be performed with the deep vacuum levels below 1×10^{-4} Torr (instead of the 0.1 psi used for habitable volume/pressurized environments). Alternatively, the thermal cycles and vacuum environment tests can be performed independently.

If the acceptance test vibration levels and spectra used to screen cells for manufacturing defects are not enveloped by the mission vibration levels, a separate qualification for acceptance vibration test (AVT) should be performed to verify that the screening levels do not degrade cell reliability.

The qualification batteries should pass all cell and battery acceptance tests as described in Section 4.2.3 prior subjecting them to qualification tests.

For custom battery designs, safety (abuse) testing performed during engineering evaluation should be repeated at qualification with pass/fail criteria for the qualification tests determined based on information derived during engineering evaluation.

- c. Flight cell lot destructive testing shall consume a randomly selected sample size that is, at minimum, 3 percent of the flight lot size or three cells, whichever is greater for each destructive test. The destructive test sample size need not exceed 350 cells.

This is to adequately populate the test matrix necessary to confirm critical safety and performance characteristics, especially those features that are critical for mission and crew safety. For COTS batteries, cells can be obtained from the disassembly of a sample from the battery flight lot. To achieve statistically significant results, all initial destructive tests must be populated with a minimum of three cells. The maximum sample size was established to define as a reasonable limit.

- d. The operation of cell safety devices, if used as a control at the battery level, shall be verified by a qualification test at the battery level or at a level that accurately simulates the level at which the control is required to confirm the operation of the safety device.

The pass/fail criteria for these qualification tests should be established after engineering evaluation tests are completed.

- e. To verify cell manufacturing quality does not vary within the lot, cell lot destructive testing shall include a minimum of 3 randomly selected cells (or 3 cells from 1 randomly selected COTS battery) that has passed cell (or battery) acceptance screening.

The cell/battery should be downgraded from flight class to uncontrolled class prior to the DPA. Supporting the DPA with a prior CT scan examination is recommended. The pass/fail criteria for the DPA should be established after the engineering DPAs are completed. Variation of components and methods used in cell construction can be detected by DPA and are grounds for lot rejection.

- f. Qualification testing shall be performed at the battery level, using flight equivalent builds.

Multiple qualification units may be used to run different tests in parallel. Tests may be re-sequenced to accommodate schedule and resource constraints as long as the intent of the test is not compromised.

Battery designs deemed non-critical need only provide verification evidence as required to complete the Unique Hazard Report for the subject battery system.

4.2.3 Acceptance Testing

This section addresses the acceptance testing of the flight battery.

- a. Cell lots intended for custom flight batteries shall undergo 100-percent acceptance screening that includes, at minimum, visual inspection of bare cell with shrink wrap removed if present, mass, OCV retention, alternating current (AC) and direct current (DC) resistance.

Work Instruction EP-WI-031 provides an example of OCV retention screen.

- b. Batteries intended for flight shall undergo flight acceptance (nondestructive) testing, which will include an evaluation of OCV, mass, capacity (for rechargeable chemistries) or load check (for primaries), internal resistance, visual inspection, vibration to flight acceptance levels, and thermal/vacuum testing.

As a minimum, the flight acceptance test program should include the following:

1. *Functional baseline test (OCV, mass, capacity (for rechargeable chemistries or load check for primaries), internal resistance, and visual inspection).*
2. *Vibration to flight acceptance levels (see Appendix A for more details).*
3. *Functional baseline test recheck.*
4. *Vacuum (approx. 0.1 psi) or equivalent leak checks.*
5. *Functional baseline test recheck.*

For batteries used in a pressurized volume or environment, exposure to a vacuum environment (approximately 0.1 psi) for a minimum of 6 hours.

For batteries used in an unpressurized volume or environment, thermal vacuum cycles must be performed with the deep vacuum levels below 1×10^{-4} Torr (instead of the 0.1 psi used for habitable volume/pressurized environments).

Alternatively, the thermal cycles and vacuum environment tests can be performed independently.

Details of recommended flight acceptance tests are provided under each battery chemistry section in Section 6 with a detailed example in Section 6's lithium-ion section. For those chemistries not listed in Section 6, early consultation with program technical staff is recommended.

Battery designs deemed non-critical need only provide cell verification in the form of UL (or similar) certification data or acceptance test results, battery system functional performance, and verification of hazard control features.

4.3 Manufacturing Quality

This section contains quality related provisions on the manufacturing lot and is intended to outline certain key aspects of manufacturing quality.

4.3.1 Configuration Control

Custom cell and battery designs intended for flight shall only be procured from vendors with configuration control processes approved by the NASA or International Partner program.

Configuration control is adequate when the manufacturer maintains documentation that enables control and replication of all tools, fixtures, machines, instruments, settings, environmental conditions, contaminant mitigation measures, materials, and pass/fail criteria for the production of a unique cell/battery design. This includes periodic independent verification of the certificates of compliance and/or analyses to meet required specifications for composition, impurities, and properties of materials and components. Configuration control requires complete two-way traceability, which is defined as documentation that demonstrates a solid chain of custody from incoming materials to final assembly and vice versa.

Custom and critical battery system designs should have independent material verifications by the cell manufacturer or customer (NASA or NASA contractor). Non-critical battery designs can rely on UL certification or international standard verification to insure configuration control. In no situation is the manufacturer specification sheet a viable form of cell performance verification.

4.3.2 Subsequent Flight Lot Testing

Some applications could require additional lots of flight batteries/cells beyond the original lot that was acceptance tested, qualified, and approved for flight. Key safety features must be retested to be sure that the new cell lots are performing like the previous qualified lot.

- a. Any new COTS battery lot and/or cell date code shall require a repeat of all battery and/or cell lot qualification testing and mitigation measures specified in Section 4.2.2.

An exception can be made for COTS cell batches delivered with two date codes that represent consecutive days if it can be verified the two days spanned a single production run.

- b. Subsequent flight cell lot destructive testing shall confirm that subsequent lot performance and safety features are the same as that of the original qualification lot.

A key purpose of this repetition is to gain confidence that configuration control of the manufacturing process is still effective and that the new cell lots are performing like the previous qualified lot. For example, if a cell internal fusible link is used as a control for external short circuit hazards, sample cells from each subsequent lot should be tested to confirm that the fusible link works as expected.

Lot sample testing is carried out to confirm that the safety tolerances of the cells/batteries remain the same compared with the original lot. A statistically significant

number of cells/batteries should be randomly selected for lot sample testing and should be based on the flight program, the number of cells manufactured, the period between manufacturing of the lots, the original materials that go into the manufacturing of a single lot, etc. A 3- to 6-percent sample size has been used for past flight battery programs.

For cell designs with configuration control, subsequent flight lot destructive testing can consist of a reduced set of lot sample testing but should include computed tomography (CT)/DPA, capacity (primary), 100-percent depth of discharge (DoD) cycle life (rechargeable), ARC or similar method (lithium), short circuit, and overcharge (rechargeable).

4.4 General Design Requirements

The following design requirements are general in nature. They are generally applicable to all battery builds.

4.4.1 Electrical Interconnection

The solid interconnection of cells to make up the battery is crucial in preventing ohmic heating, which would result in reduced performance and/or life and may result in a hazardous overheating of cells within the battery.

- a. The electrical interconnections that form the pack through the interconnection of cells shall be made of low-resistance connections such that ohmic heating at the design load presents no over-temperature hazard.
- b. The means of interconnection (i.e., mechanical fasteners, tack weld, etc.) and its verification shall ensure that the flight environments and usage profile do not reduce the effectiveness of the connection.

In the case of bus bar interconnections via threaded fasteners, flight vibration as well as thermal variation over the course of the load profile would tend to loosen the connection. Torqueing requirements coupled with fastener locking features are necessary to ensure the effectiveness of the connection throughout the mission (reference NASA-STD-5020, "Requirements for Threaded Fastening Systems in Spaceflight Hardware," for best practices).

4.4.2 Electrical Wiring

The integrity of wire and the insulation used within the battery must be ensured.

- a. Wiring used within the flight battery shall adhere to Electrical Wire and Cable Acceptance Tests described in JSC-STD-8080.5 E-24 or be certified via an equivalent standard.

4.4.3 Lithium-ion Battery and Cell Monitoring

For lithium-ion batteries, monitoring of key parameters such as cell/battery voltages, cell temperature, and battery/string current is necessary to ascertain health and maintain safe operation of the battery. Monitoring of pertinent parameters may show adverse trends in the state of health and can be essential to investigating failures within the battery.

- a. For custom or COTS batteries with catastrophic failure modes due to cell under/over voltage, monitoring shall be provided in order to detect and control hazardous under/over voltage of any cell in the battery.

The requirements here seek to strike a balance between monitoring required for safety and the reliability of the battery and accompanying instrumentation.

- b. For custom or COTS batteries with catastrophic failure modes due to high currents, battery-level current monitoring shall be provided in order to detect and control hazardous currents in the battery.

- c. For custom or COTS batteries with catastrophic failure modes due to high/low temperatures, temperature monitoring shall be provided to detect and control hazardous temperatures at any cell in the battery.

Optimal number and placement of the temperature sensors to provide adequate coverage for all cells should be based on high-fidelity thermal analysis for nominal and off-nominal conditions.

- d. For custom battery designs with catastrophic failure modes, instrumentation shall collect data during use and during charge and be reviewable on the ground for use in trending and/or post anomaly analysis.

The requirements above focus on key measurements and time periods for monitoring. For example, a requirement to monitor key parameters even when not in use (i.e., on the shelf) may be prohibitive (i.e., may drive a monitoring system that is self-powered and self-contained within the battery) and yield other adverse effects. Similarly, for the purpose of trending, it is acceptable to only monitor/record key parameters before, during, and after each charge to increase simplicity and reliability the battery for the discharge phase.

4.4.4 Cell Matching

Cell performance matching for selection into batteries is a useful practice in custom battery builds when done in addition to cell acceptance screening specified in Section 4.2.3b.

- a. For custom batteries with catastrophic failure modes, cell performance matching prior to battery assembly shall be performed to mitigate state-of-charge (SOC) imbalances that could adversely affect battery performance and/or safety.
- b. For custom batteries with catastrophic failure modes, cells shall be matched in a battery based on charge retention, internal resistance and/or AC impedance, and ampere-hour capacity (for rechargeable chemistries).

The requirements above prescribe a matching protocol intended to select from the acceptance screened lot of cells. These requirements are not a remedy for poor lot uniformity. Note that cell matching and the use of balancing circuits should not be rationale for accepting lots with poor cell lot uniformity, which indicates a less controlled manufacturing process and may indicate product with a higher likelihood of rapid degradation of field performance.

4.4.5 Dissimilar Controls

For battery chemistries with catastrophic failure modes due to excessive charge or discharge (including external short circuit), software-based controls to mitigate these hazards are more and more common. These controllers manage the charging and discharging of the battery within safe parameters and can be located in the battery charger, the power distribution system, and/or the battery itself.

- a. For custom batteries with catastrophic failure modes, software-based controls responsible for managing the charge/discharge of the battery shall operate inside a safe envelope maintained by active or passive hardware-based controls and guards.
- b. For custom batteries with catastrophic failure modes, in cases where software-based controls are not enveloped by hardware controls, the software is safety critical and its development shall include conventional software assurance processes and confidence not based solely on integrated testing.

Where computer based controls are used, applicable safety requirements (SSP 50038) will need to be met.

4.5 Mission Usage

- a. During the preparation phase for on-orbit processing, the hardware owner shall provide details for safe operation of the hardware on-orbit, any on-orbit processing that may be required, and safe stowage or disposal.
- b. The hardware owner shall establish on-orbit processes and operational constraints in coordination with the mission controllers for the hardware.

Provide on-orbit processes that may include procedures for hardware inspection and checkout that are required prior to on-orbit usage of the equipment.

Provide procedures to dispose of depleted cell(s) and batteries and replace them if the battery-powered applications are designed for on-orbit replacement.

Provide procedures for recharging, re-installing, and storing rechargeable cells and batteries if the application is designed for rechargeable cells or batteries.

Provide procedures to remove, visually inspect, tape, and bag depleted or discrepant cells and battery packs and place them in dry trash.

NOTE: For cells and batteries that are returned as trash on Russian vehicles, the requirements given in P32928-103, "Requirement for International Partner Cargoes Transported on Russian Progress and Soyuz Vehicles," are followed.

Crew members should record anomalies during any phase of battery use from installation and usage through removal/recharge to storage/disposal.

- c. For the custom lithium-ion battery designs that are designated as catastrophic (see 4.1.3) and required to be used in a crewed environment for more than 1 year or for multiple missions requiring launch and landing, the health of the battery shall be monitored to allow insight into changes that could lead to a catastrophic failure.

The long-term physical and chemical changes associated with the cells and internal construction of the batteries are not typically fully understood when a custom-designed battery is flown for space application; hence, it is imperative to

monitor the health of the battery. Techniques such as thermography when the battery is under load can provide information on bad welds or electrical connections; unique discharge loads with a high current pulse inserted to provide internal resistance measurements can also provide a warning to changes that may lead to a catastrophic failure.

A fleet leader may be provided on ground to monitor and characterize the health and physical appearance of the battery. The fleet leader should have storage and operating time and cycles, with margin, in excess of the flight units to provide confidence that any anomalous behavior may be detected prior to occurring in flight.

4.6 Post-flight Cell and Pack Evaluation

- a. A post-flight performance evaluation of the hardware and the batteries shall be conducted when hardware is returned post-flight.
- b. For cells and batteries installed in hardware during return flight, after the post-flight evaluation, the cells and battery pack shall be removed so that the equipment may be stored without the cells and pack installed.

An exception is made for coin cells that provide memory storage for hardware. Cells providing memory storage need not be removed unless performance degradation has been noted, the shelf life has expired, or signs of damage or corrosion are evident.

For additional information, battery storage is defined in JSC 26549, "JSC Manual for Control of Program Stock." Details regarding the process for post-flight removal of cells or battery packs are provided in JWI 8705.3.

4.7 Ground Processing Requirements

Battery systems intended for crewed spacecraft must maintain safety during ground handling, transportation, and ground operations. While this document contains a number of items that should be considered to ensure safety of ground battery operations and handling, the subset listed in this section is considered necessary and contains requirements to ensure safe operation.

- a. The hardware developer or provider shall establish protocols and controls to address identified hazards and document those processes in the safety data package prepared for the system.
- b. Battery system transportation shall be in accord with domestic and international regulations.

4.7.1 Requirements for Ground Handling and Transportation

- a. Sufficient ventilation shall be provided when processing non-sealed batteries to ensure that the concentrations of electrolyte vapors, combustible gases, or toxic gases do not reach 50 percent of the lower exposure limit (LEL).
- b. Ground handling and transportation shall be in accordance with JPR 1700.1, "JSC Safety and Health Handbook," or equivalent standards.

Ground handling and transportation best practices include:

- a. Battery test benches and tables should be coated with electrolyte-impervious coatings.*
- b. The battery test areas should have a designated eye wash station and shower.*
- c. Shock sensors should be installed on containers transporting cells and batteries (typically classified as Hazardous Material (HAZMAT) Class 9 by 49 CFR).*
- d. Temperature sensors should be installed on containers transporting cells and batteries (typically classified as HAZMAT Class 9 by 49 CFR).*

JWI 8705.3, "Battery Processing," contains excellent guidance regarding ground handling.

4.7.2 Design and Operations Requirements for Ground Support Equipment

Ground support equipment (GSE) consists of the non-flight systems, equipment, or devices (with a physical or functional interface with flight hardware) necessary to routinely support the operation of transporting, receiving, handling, assembly, inspection, test, checkout, and servicing of flight hardware.

- a. GSE for batteries shall be designed such that the combination of the battery and GSE does not reduce the level of failure tolerance intended in the flight battery design.

Equipment used to test or charge batteries should have redundant controls in place, including dissimilar redundancy to prevent hazards due to malfunction of test equipment.

Best practices in GSE design include but are not limited to:

- a. The polarity of GSE connecting to battery terminals should be keyed.*
- b. For external chargers, the specification document for the charger should be used as guidance for the build and test procedures.*
- c. COTS GSE should not be modified without GSE manufacturer's recommendations and approval.*
- d. All test equipment, especially those interfacing with flight batteries, should be calibrated periodically as required by the equipment manufacturer. Verification of calibration should be confirmed before the start of test so that no calibration will be required during the test program.*
- e. Test protocols programmed into the GSE should have tolerance ranges for all the parameters used for charging or operation.*
- f. Test protocols programmed into the GSE should have design limits specified for the test parameters.*
- g. Test protocols programmed into the GSE should have safety limits specified for the test program.*

- h. The test equipment should be designed with limits that prevent restart of equipment or continuation of the test in the event of power, test equipment, or battery failures.*
- i. Safety devices and mandatory verification steps should be incorporated into the GSE designs and handling/operating procedures, especially where failure tolerance is not met by the battery system alone.*
- j. GSE should be verified to operate safely prior to connecting a battery to it.*
- k. Uninterrupted power supply should be provided for all GSE that involves critical testing, such as testing of flight batteries.*
- l. Battery test equipment should be internally protected against short circuits.*
- m. Battery test equipment should not impose short circuits on the test article.*
- n. Access to emergency eye wash, shower, or combination units for the battery charging and conditioning area should not be obstructed and should be no more than 25 feet distant or 10 seconds travel time from the battery test area.*
- o. Personnel involved with handling, testing, installing, or any other battery-related operations should be trained as required in the specific battery chemistry safety. Test team personnel should receive daily briefings on the tasks to be carried out each day with an emphasis on safety.*
- p. All battery storage should be in accordance with the manufacturer's specification and Safety Data Sheets (SDS).*
- q. A Lith-X or Class ABC fire extinguisher, as required per the SDS of the batteries, should be available in the test location.*

4.8 Shelf and Service Life Related Requirements

- a. Shelf and service life of batteries shall be tracked.*
Appendix C provides further details on the shelf life and service life of various commonly used cell chemistries.

5. GENERAL BATTERY HAZARDS AND CONTROLS

Potential hazards and safe design requirements are discussed in this section. Hazard sources are identified, hazard manifestations are explained, and hazard prevention and control requirements are presented. Not all controls will apply to all battery designs; hence, thorough identification of hazards and controls is required to prove design safety.

At minimum, fire/explosion, chemical exposure, electrical shock, and touch temperature are battery hazards to crewed spacecraft and crew.

Requirements:

- a. The possible sources of battery hazards shall be identified for each battery design while considering the entire set of mission phases and conditions.
- b. Each hazard shall be evaluated to determine applicability and to identify all sources, which can be broadly categorized as inadequate design, poor workmanship, and/or abuse (electrical, mechanical, and/or thermal).
See Section 6 for details of chemistry-specific battery hazard sources.
- c. The hazard severity shall be categorized as catastrophic, critical, or non-critical.

5.1 Fire/Explosion Hazard

Fire and/or explosion hazards can result from the generation and ignition of a combustible gas mixture, evolution of large quantities of free gases, or initiation of a runaway internal reaction in a cell (thermal runaway). Excessive internal pressure (either within cell or battery enclosure) can result in failure of cell and/or battery seals and cases. Cell and/or battery contents can then be expelled from the cell, either slowly or forcibly. Shrapnel fragments from violent cell or battery enclosure bursting can cause damage upon impact to personnel, structure, or equipment.

5.1.1 Sources – Chemical Reaction

1. Some batteries generate hydrogen and/or oxygen while discharging and/or charging. Hydrogen gas, mixed with air or oxygen, is flammable and/or explosive over a concentration range of 4 percent to 75 percent by volume in air.
2. Many aqueous electrolyte cells subjected to charging will generate oxygen as the charge nears completion, providing oxygen where none may have existed previously, such as in a battery container that had been purged with nitrogen to flush away oxygen.
3. Accumulation of gases in a sealed cell or battery case can build up pressure within the case.
4. A plugged or faulty pressure relief valve in a cell or battery enclosure.