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NASA Aerospace Flight Battery Program

Recommendations for Technical Requirements for Inclusion in Aerospace Battery Procurements

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August 2010

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Volume I: Technical Assessment Report

NASA Aerospace Flight Battery Program

Part 2: Recommendations for Technical Requirements for Inclusion in Aerospace Battery Procurements

February 18, 2010

Report Approval and Revision History

NOTE: This document was approved at the February 18, 2010, NRB. This document was submitted to the NESC Director on February 23, 2010, for configuration control.

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1.0	Initial Release	Ms. Michelle A. Manzo, Chief, Electrochemistry Branch, Glenn Research Center	02/18/10

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1.0 Notification and Authorization

The National Aeronautics and Space Administration (NASA) Aerospace Flight Battery Systems Working Group (NAFBSWG) was chartered within the NASA Engineering and Safety Center (NESC) on October 5, 2006. Under this charter, NAFBSWG was authorized by Mr. Ralph R. Roe, the NESC Director, at the NESC Review Board (NRB) to develop an annual plan to address critical battery-related issues for the Agency and the aerospace community. Ms. Michelle Manzo, Chief of the Electrochemistry Branch at Glenn Research Center (GRC), serves as Chair of the NAFBSWG.

The Initial Plan was presented to the NRB on January 25, 2007. It involved a series of tasks addressing pressing issues related to aerospace battery implementation. The Final Report for Year 1 (Part 1) was approved by the NRB on July 10, 2008. The Final Report for Year 1 (Parts 2 and 3, Volumes I and II each) were approved by the NRB on February 18, 2010.

The key stakeholders for this assessment are the Exploration Systems Mission Directorate (ESMD), Science Mission Directorate (SMD), and Space Operations Mission Directorate (SOMD).

2.0 Signature Page

Submitted by:

Team Signature Page on File – 5/24/10

Mr. David S. Jung	Date	Ms. Michelle A. Manzo	Date

Significant Contributor:

Dr. Hari Vaidynathan	Date

Signatories declare the findings and observations complied in the report are factually based from data extracted from Program/Project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analysis, and inspections.

3.0 Team List

Name	Discipline	Organization/Location
Core Team		
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Terri Derby	Project Coordinator	LaRC/ATK
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Carolyn Snare	Technical Writer	LaRC/ATK

3.1 Acknowledgements

In Memoriam: This report is dedicated to the memory of our dear colleague Dr. Gopalakrishna (Gopal) Rao. Dr. Rao supported the Power Systems Branch at Goddard Space Flight Center (GSFC) for 19 years until his untimely death on May 15, 2008.

GSFC, under Dr. Rao's leadership, was the implementing organization for this task. Mr. David Jung, Dr. Hari Viadyanathan, and Ms. Michelle Manzo completed this report after Dr. Rao's passing.

The assessment team would like to specifically acknowledge contributions from the following:

- Financial/Contracting: Ms. Pam Throckmorton
- The support team from Alliant Techsystems, Inc. (ATK) at Langley Research Center (LaRC) provided excellent support: Ms. Terri Derby for her efforts in meeting

[1] Dr. Gopalakrishna Rao served as a core member of this team until his death on May 15, 2008.

coordination and documentation, and Ms. Carolyn Snare and Mr. Eric Pope for technical editing

- Peer Reviewers: Mr. Mitchell Davis, Mr. George Dakermanji, Mr. Steve Gentz, Mr. Denney Keys, Dr. Chris Iannello, and Mr. Tim Trenkle

4.0 Executive Summary

In the summer of 2006, the NASA Engineering and Safety Center (NESC) requested that all Super Problem Resolution Teams (SPRTs) (now called Technical Discipline Teams (TDTs)) be solicited for proposals for Discipline Advancing work. Guidance for proposals included the identification of tasks which address activities that no single program/organization may be able (or reasonably expected) to fund, but where critical knowledge (such as fundamental understanding, a specification, basis for risk assessment, etc.) was lacking. The NASA Aerospace Flight Battery Systems Steering Committee was approached to develop a response to this request. Relevant battery-system issues of concern were identified and prioritized. Tasks aimed at addressing the most critical of these persistent, Agency-wide technical problems were identified. These tasks became the basis of the proposal (NESC PL-07-02/06-069-I: NASA Aerospace Flight Battery Systems Working Group (NAFBSWG) Annual Plan) that was accepted by the NESC Review Board (NRB) on October 5, 2006.

At the same time, the NAFBSWG was chartered within the NESC. The NAFBSWG was tasked to complete these tasks, and to propose future work to address battery-related, Agency-wide issues on an annual basis. In its first year of operation, this effort addressed various aspects of the validation and verification (V&V) of aerospace battery systems for NASA missions. NAFBSWG members performed studies, discussed issues, and in many cases, tested programs to generate recommendations and guidelines to reduce risk associated with implementing battery technology in the aerospace industry.

The reporting on these tasks has been split into three Parts, as identified below[2]. The subsequent Final Report for this assessment has also been split into three documents, one for each Part:

1) Part 1: Generic Safety, Handling, and Qualification Guidelines for Lithium-Ion (Li-Ion) Batteries (NESC Report Number RP-08-75) :
    a. Li-Ion Performance Assessment.
    b. Generation of a Guidelines Document that Addresses Safety and Handling and Qualification of Li-Ion Batteries (a general guidelines document was developed that was supplemented by the following studies addressing specific Li-Ion batteries concerns).
        i. Definition of Conditions Required for Using Pouch Cells in Aerospace Missions.

[2] Current order of outline and Part numbers are different from original outline in Part 1 of Final Report. Part 1 is now Part 2, Part 2 is now Part 3, and Part 3 is now Part 1. The current Final Report Part 1 documents (Vols. I and II), follow the updated order, reflected in the outline shown above.

ii. High-Voltage Risk Assessment: Limitations of Internal Protective Devices in High-Voltage/High-Capacity Batteries using Li-Ion Cylindrical Commercial Cell.

iii. Definition of Safe Limits for Charging Li-Ion Cells.

c. Availability of Source Materials for Li-Ion Batteries.

d. Technical Communications Related to Aerospace Batteries (NASA Battery Workshop).

2) **Part 2: Recommendations for Technical Requirements for Inclusion in Aerospace Battery Procurements**[3]

3) Part 3: Wet Life of Nickel-Hydrogen ($Ni\text{-}H_2$) Batteries.

This document is Part 2 of the Final Report and focuses on Recommendations for Technical Requirements for Inclusion in Aerospace Battery Procurements. Assessment 06-069-I Final Report Part 1 is complete and has been catalogued as NESC Report RP-08-75. All three Parts of the Final Report collectively present the results of the NAFBSWG efforts that were initiated in Fiscal Year 2007.

4.1 Part 2: Recommendations for Technical Requirements for Inclusion in Aerospace Battery Procurements

For many NASA missions, the power system is purchased as a package that is separately integrated into the spacecraft. The battery specifications for this package generally include only top-level functional requirements related to the battery system (i.e., performance-based requirements). The high-level specifications often result in limited visibility into the manufacturing process and cell and battery handling. This limited access to data on critical processes such as cell activation and cell balancing, combined with unspecified conditions for reconditioning, temperature limits, and storage conditions, places the NASA technical community at a disadvantage and limits their ability to ensure the battery will perform to meet mission requirements.

In recent missions, such as Tracking and Data Relay Satellite (TDRS), Cloud-Aerosol Light Detection and Ranging Instrument (LIDAR) and Infrared Pathfinder Satellite Observations (CALIPSO), and Geostationary Operational Environmental Satellite (GOES), the problems associated with limited insight became an issue when performance issues arose and prompted NASA interventions at the launch readiness phase that resulted in costly launch delays. These problems could have been mitigated had the battery procurement included detailed technical specifications and requirements that addressed performance, handling, and storage.

[3] Title formally identified as Recommendations for Binding Procurements.

4.1.1 Proposed Solution

Develop recommendations for aerospace batteries which outline the technical requirements, data deliverables, and critical processes that require oversight in order to be considered for inclusion in the procurement documents of a satellite power system.

4.1.2 Mitigation

A set of recommendations outlining elements to be considered for inclusion in battery procurements was generated to ensure that NASA has the data and insight into processes related to battery development, delivery, and handling. These battery system recommendations will be made available for consideration at the procurement initiation for a satellite power system. Adopting these recommendations would ensure that minimum requirements (from a NASA battery system engineering perspective) would be addressed and provide greater involvement and definition of the battery portion of the power system. It will help reduce overall costs and mitigate risks from the NASA perspective. The recommendations call for a greater level of NASA involvement in specification design, verification, qualification, and use of batteries. NESC recommendations, directed toward future Programs and Projects that will use aerospace batteries, are summarized below:

- Identified aerospace battery technical requirements contained herein should be considered for inclusion in the initial procurement package/contract.
- NASA should verify/confirm that contractors and their sub-contractors are complying with NASA standards of workmanship.
- A cell-level manufacturing control document (MCD) containing the items listed below should be provided to NASA for review and approval. Approval is required for the original document and any subsequent modifications that affect the relevant cell build.
    - Cell design data
    - Composition of electrodes and electrolytes
    - Source material specification and history
    - Mechanical cell part specification and tracking
    - Process descriptions and controls
    - Procedure for cell activation
- Manufacturing plant audits and additional lot level screening can be considered as alternates to the MCD insight for batteries that are fabricated from commercial-off-the-shelf (COTS) cells.

- A battery-level MCD containing the items listed below should be provided to NASA for review and approval. Approval is required for the original document and any subsequent modifications that affect the relevant cell build.
    - Battery design data
    - Cell specifications
    - Battery product information, mechanical cell parts
    - Procedure for cell matching and selection
- A battery-handling plan that addresses the items below should be provided by the contractor to NASA for review and approval:
    - Storage and transportation
    - Temperature limits during inactive periods
    - Reconditioning procedures and sequence
    - Procedures for managing charge/discharge and storage of the batteries if the launch is postponed
- Delivery of the defined data and information (MCD and handling plan) should occur at least one week prior to review meetings to allow NASA sufficient time for review and approval.

5.0 Assessment Plan

The NAFBSWG provided a framework to address manufacturing and performance issues related to flight-battery systems technology and applications for NASA missions that require batteries. This assessment supported the V&V of aerospace-battery systems for NASA missions. It enabled the implementation and execution of critical test programs to reduce risk by addressing wide-ranging technology issues. These issues affect the safety and success of future NASA missions.

The objectives of the NAFBSWG are:

- Develop, maintain, and provide tools for the validation of aerospace battery technologies.
- Accelerate the readiness of technology advances and provide infusion paths for emerging technologies.
- Provide the database and guidelines for technology selection that can be used across mission directorates.
- Disseminate validation and assessment tools, along with quality assurance and availability information, to the NASA and aerospace battery communities.
- Provide problem-resolution expertise and capability within the Agency and the aerospace community.

During this assessment, it was determined that the analysis could be split into three distinct parts[4]:

1. Part 1: Generic Safety, Handling, and Qualification Guidelines for Lithium-Ion (Li-Ion) Batteries (NESC Report Number RP-08-75)
2. **Part 2: Recommendations for Technical Requirements for Inclusion in Aerospace Battery Procurements**[5]
3. Part 3: Wet Life of Nickel-Hydrogen (Ni-H_2) Batteries

As a result, the final report was also divided into three separate documents, each addressing one of the three Parts. This document addresses **Part 2.**

Dr. Gopalakrishna Rao and later, Mr. David Jung, served as Lead for the generation of technical recommendations for inclusion in aerospace battery procurements (presented in the Final Report, Part 2). Lockheed Martin (LM)-Communications Satellite (COMSAT) Technical Services was tasked through NESC funding to assist in the document preparation.

[4] Current order of outline and Part numbers are different from original outline in Part 1 of Final Report. Part 1 is now Part 2, Part 2 is now Part 3, and Part 3 is now Part 1. The current Final Report Part 1 documents (Vols. I and II), follow the updated order, reflected in the outline shown above.

[5] Title formally identified as Recommendations for Binding Procurements.

The technical approach for Part 2 consisted of:

- Review of current procurement practices for batteries.
- Discussions with NASA Project and Center technical personnel.
- Development/identification of example procedures, relevant for charge/discharge and for storage and handling, that include launch site and transportation practices.
- Determination of the adequacy of data/information to develop on-orbit battery management and to resolve on-orbit anomalies.
- Development of procurement guidelines for incorporation into technical requirements for inclusion in aerospace battery procurements for power systems.

6.0 Problem Description and Proposed Solutions

6.1 Problem Description

In the past, NASA has acquired batteries in the form of a power system package for integration into the spacecraft. This type of performance-based procurement has a drawback, as it addresses only top-level performance specifications and provides limited visibility into obtaining battery-handling procedures during processing and integration and at the launch site. Without such definition, it is not uncommon for the opinion of NASA engineers related to battery handling to differ from that of the battery manufacturers. This often resulted in protracted discussions about processes and procedures related to battery handling. From a contractor's perspective, technical decisions may focus on demonstrating the minimum performance requirements while minimizing costs. In contrast, NASA is interested in ensuring long-term performance that could be compromised by improper handling or enhanced by special handling.

NASA engineers responsible for the batteries on programs like TDRS, GOES, and CALIPSO faced insufficient technical information regarding battery handling, storage, and reconditioning prior to launch.

CALIPSO is a collaboration between LaRC and the French Space Agency, Centre National d'Etudes Spatiale. LaRC serves as the lead for the mission and provides overall program management, systems engineering, payload missions operations, science data validation, and data processing and archival. GSFC, as direct technical support to LaRC, provides program management and launch oversight for the CALIPSO mission. During mission development, GSFC had limited visibility into the definition of the battery system. This was one of the first NASA missions to use Li-Ion batteries and as such, detailed knowledge and approval of the battery handling plan were critical to the safety and success of the mission. The limited access to this information impeded preparations for the launch.

For the GOES Mission, insufficient or nonexistent documentation related to battery reconditioning led to disagreements regarding the specifics of the schedules, methods, and support. Similarly, lack of specification on how the battery should be handled during launch delays led to debates related to the state-of-charge, the recovery method to be employed after extended open circuit stands, the identification of what telemetry should be monitored, and what values/limits should be set for action (e.g., cell voltage spread, end-of-discharge voltages, temperatures, pressures). These factors were not identified until weeks before the launch and vehicle delays required the GOES Project to direct the contractor to initiate actions that the contractor felt were unnecessary. This led to disagreements between the contracted GOES Project management and NASA engineering that required Agency (Headquarters) intervention.

The issues previously noted could have been minimized had there been defined technical requirements in place for the batteries and their handling. The effort described in this document provides a set of recommendations to guide contract document preparation for procuring Ni-H_2 and Li-Ion batteries for aerospace applications to avoid the potential pitfalls and problems related to the lack of in-depth specifications regarding battery processing, performance, and handling.

Ni-H_2 and Li-Ion batteries have been flight tested in a number of missions. As the more mature technology, Ni-H_2 has a well-documented history related to design specifications for specific mission types. Through experience, certain sizes and capacities have been qualified and inappropriate cell designs have been rejected. This extensive experience with Ni-H_2 batteries provided the basis for the recommendations identified in this document.

At present, the procurement document for aerospace batteries as part of the power system includes a specification for the batteries, statement of work, deliverable items list, and schedule milestones. There is a need for a more detailed statement of work that provides for more frequent and more detailed inspections of the cells and batteries during construction and generally more insight into the processes at the manufacturer's plant. Document delivery must occur at least a week before the major design reviews (Preliminary and Critical Design) to provide adequate time for review.

Acceptance procedures have been developed that are refined for each mission; introducing specificity, identifying constraints, and elaborating electrochemical and thermal properties. This level of customization is not achieved with performance-based spacecraft bus procurement requirements.

For Ni-H_2 cells, there are currently a number of options for the cell design (e.g., anode and cathode compositions, configuration, active core, electrolyte composition, seals, etc.) and the advantages and limitations of these options are documented. There have been cell builds where manufacturing problems and poor workmanship contributed to anomalous performance that resulted in delayed completions of hardware and cost overruns. Customers and in-house engineering staff of the cell/battery manufacturers inspected the manufacturing steps and unearthed and resolved many problems that had surfaced for Ni-H_2 and Li-Ion batteries. In past missions there are examples where batteries were exposed to high-temperature excursions or cell reversal during battery testing. These types of problems require special handling for recovery and can manifest as performance issues later in life. Knowledge of this type of information is critical to the long-term handling of batteries in order to maximize performance for NASA missions.

6.2 Proposed Solution

The fabrication and delivery of batteries for aerospace applications consist of several steps, including preparation of the performance, manufacturing, qualification, and test specifications for the individual cells and the battery; sequencing of the design, readiness, and acceptance reviews; and scheduling the manufacturing, assembly, documentation, and final delivery of various components. The contract document for the vendor should specify the delivery details for various documents and the final product. The most important element in the contract documentation is the inclusion of mandatory inspection points that address battery manufacturing and test procedures, including sequencing steps in the manufacturing process, and application of approved manufacturing procedures. Experience points to the fact that this enhanced visibility into the manufacturing process by NASA experts aids in the identification and resolution of problems in the early stages, before they can result in costly launch delays.

The implementation of recommendations for the battery system that cover cell design; acceptance and qualification tests; cell buyoff; cell receipt and handling instructions; and special tests such as reconditioning, rejuvenation, and cell storage conditions will provide the increased visibility to address issues throughout the process.

COTS cells are currently being used in aerospace battery builds. In these cases, the cell-level manufacturing controls required for aerospace cell manufacturing are not practical. These practices can be replaced with additional cell-level screening tests and manufacturing plant audits to ensure the fidelity of the practices for the cells under consideration.

7.0 Data Analysis

A summary of the efforts involved in developing the Recommendations for Technical Requirements for Inclusion in Aerospace Battery Procurements follows:

- Review of current procurement practices for batteries.

  Discussions of issues with NASA Project and Center technical personnel. The design, schematics, manufacturing and test procedures, compliance matrix, and timely delivery of test data and hardware were addressed. As part of the work, discussions were held with Ms. Michelle Manzo (GRC); Dr. Judith Jeevarajan (Johnson Space Center (JSC)); Dr. Ratnakumar Bugga (Jet Propulsion Laboratory (JPL)); Dr. Margot Wasz (The Aerospace Corporation (TAC)); Mr. Leonine Lee, Ms. Diane Yun, Dr. P.R.K Chetty, Mr. Ronald Zaleski, and Mr. Joseph Springer (GSFC).

- Development/identification of example procedures, relevant for charge/discharge and storage and handling, that include launch site and transportation practices. During the generation of this report, the HST Ni-H_2 Battery and Battery Module Handling Plan (see Appendix A of Volume II) was identified as an example of a well-documented practice.
- Determination of the adequacy of data/information to develop in-orbit battery management and resolve in-orbit anomalies. During this assessment it was found that current practices implemented by the contractors did not always comply with NASA standard practices. The NASA standard for verification of thermal gradients in a battery in all conditions of charge/discharge for Li-Ion and Ni-H_2, nickel precharge level for Ni-H_2, low-voltage limits for resistive discharge during reconditioning for Ni-H_2, and end-of-charge voltage limits for Li-Ion with aging and cycling are not in practice and reworking of cells to meet a performance criteria is allowed but with insufficient controls.
- Development of technical requirements for inclusion in aerospace battery procurements for power systems.

  Questions were prepared to assess responses from various Government satellite facilities and obtain a better understanding of the broader requirements of the battery contract document. The questions that provided the basis of the discussions related to Ni-H_2 and Li-Ion cell procurement involved the following:

  1. Complete cell-design document including proprietary items.
  2. Cell and battery heat-dissipation characteristics during charge, discharge, and self-discharge, thermal models to predict these characteristics.
  3. Specifications of individual cell components including purchased items.
  4. Composition of the anodes, cathodes, electrolytes, and separators.
  5. Storage history of positive and negative plates and the electrolyte composition at the time of cell construction.
  6. Cell activation procedure.
  7. Cell handling and storage procedures.
  8. Gas-leakage rates of the cells.
  9. Chronology and details of charge and discharge cycles following cell activation.
  10. Reconditioning procedure after receipt of battery.
  11. Limits for voltages during charge and discharge cycles at various rates and temperatures.
  12. Predicted capacity as a function of life.

13. Cell balancing and bypass circuitry for batteries, in particular, Li-Ion batteries.
14. Extended storage for activated cells/batteries.
15. Component sample delivery for analysis.

In view of the differences in the electrochemistry of the cells, Ni-H_2 and Li-Ion batteries are handled differently during spacecraft integration and launch-site charging and reconditioning. Ni-H_2 is amenable to overcharge, tolerant of low-rate overdischarge, can sustain trickle charge for extended periods, and operates at internal pressures up to 1,200 psi with a temperature of operation range from -10 to +15°C. Li-Ion, however, cannot be overcharged or overdischarged, electrolyte conductivity decreases as the temperature decreases, which limits the operational temperature range when not using low-temperature electrolytes, cannot be trickle charged for extended periods of time, and the electrolyte is flammable and fails catastrophically if charged at high temperatures. Table 7.0-1 shows a comparison of Li-Ion and Ni-H_2 battery-handling features.

Table 7.0-1. Specifics of Battery Handling for Ni-H_2 and Li-Ion Chemistries

Item	Li-Ion	Ni-H_2
Cell balancing during operation	Required[1]	Not commonly used
Voltage clamp during charge	Required	Preferred
Extended trickle charge	Prohibited	Applicable
Operation at very low temperature	Requires customized electrolyte	Possible at −10°C
Resistive drain reconditioning	Applicable[2]	Applied to equalize the pressure and redistribute the electrolyte
Charge temperature at launch site	10 to 30°C	< 20°C
Storage during launch	< 20°C	< 20°C
Cell orientation	Limited data	Vertical preferred for some applications[3]

[1] Batteries comprised of 18650 cells may not require cell balancing during operation.

[2] Can be used but not recommended, voltage generally should not go below 2.5 volts.

[3] Recommendations for orientation differ by supplier. Boeing prefers to have their cells mounted vertically for ground tests.

8.0 Findings and NESC Recommendations

8.1 Findings

The following Findings related to current procurement practices for aerospace batteries were identified:

F-1. Current practices for procurement of spacecraft power systems specify battery requirements at a high level (i.e., performance-based).

F-2. Current battery-related practices implemented by the contractor do not always comply with NASA standards.

F-3. There is limited visibility into the documentation and the cell construction and handling processes. This lack of in-depth technical knowledge limits NASA's ability to rapidly respond to real-time issues and can result in launch delays as the contractor is brought onboard and/or NASA technical experts obtain and digest information.

8.2 NESC Recommendations

The following NESC Recommendations were identified and directed toward the key stakeholders unless otherwise identified:

R-1. Identified aerospace battery technical requirements outlined herein, should be considered for inclusion in the generation of the initial procurement package/contract. **(*F-1, F-3*)**

R-2. NASA should verify/confirm that contractors and their sub-contractors are complying with NASA standards of workmanship. **(*F-2*)**

R-3. A cell-level MCD that includes the items listed below should be provided to NASA for review and approval. Approval is required for the original document and any subsequent modifications that affect the relevant cell build: **(*F-1, F-3*)**

- Cell design data
- Composition of electrodes, electrolytes, and separators
- Source material specification and history
- Mechanical cell part specification and tracking
- Process descriptions and controls

- Procedure for cell activation/formation
- Procedure/criteria for cell matching and selection

R-4. Manufacturing plant audits and additional lot level screening can be considered as alternates to the MCD insight for batteries that are fabricated from COTS cells. **(*F-1, F-3*)**

R-5. A battery-level MCD that includes the items listed below should be provided to NASA for review and approval. Approval is required for the original document and any subsequent modifications that affect the relevant cell build: **(*F-1, F-3*)**

- Battery design data
- Cell specifications
- Battery product information, mechanical cell parts
- Procedure/criteria for cell matching and selection

R-6. A battery-*handling* plan that addresses the items below should be provided by the contractor to NASA for review and approval. **(*F-1, F-3*)**

- Storage and transportation
- Temperature limits during inactive periods
- Reconditioning procedures and sequence
- Procedures for managing charge/discharge and storage of the batteries if the launch is postponed

R-7. Delivery of the defined data and information (MCD and handling plan) should occur at least 1 week prior to review meetings to allow NASA sufficient time for review. **(*F-3*)**

9.0 Definition of Terms

Acceptance	A determination that the product meets the design specifications.
Active Core	The material in the cell that is undergoing oxidation or reduction during the electrochemical reaction.
Anode	The electrode where oxidation occurs during the electrochemical reaction during discharge.

Battery	One or more electrochemical cells that are electrically connected.
Catastrophic	Thermal runaway, venting with fire, violent venting with expulsion of cell contents, or expulsion of cell from multi-cell module configuration, resulting in loss of mission or life.
Cathode	The electrode where reduction occurs during the electrochemical reaction during discharge.
Cell	A single-unit device within one cell case that transforms chemical energy into electrical energy at characteristic voltages when discharged.
Cell Activation	The addition of electrolyte to a cell that enables the electrochemical reaction to take place.
Cell Balancing	The process of charging and discharging the cells in a battery in a manner such that they are brought closer to the same voltage levels.
Cycle	A discharge (where the capacity of the battery is used) and subsequent recharge (where the capacity of the battery is restored) of a rechargeable battery.
Electrode	The location where the electrochemical reactions occur.
Finding	A conclusion based on facts established by the investigating authority.
Insight	Surveillance mode requiring the monitoring of customer-identified metrics and contracted milestones. Insight is a continuum that can range from low intensity, such as reviewing quarterly reports, to high intensity, such as performing surveys and reviews. (Definitions from source document: NPR 8735.2, Management of Government Safety and Mission Assurance Surveillance Functions for NASA Contracts.) NPR 7150.2 NASA Software Engineering Requirements, APPENDIX B: Definitions.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.

Observation	A factor, event, or circumstance identified during the assessment that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. Alternatively, an observation could be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Oversight	Surveillance mode that is in line with the supplier's processes. The customer retains and exercises the right to concur or nonconcur with the supplier's decisions. Nonconcurrence must be resolved before the supplier can proceed. Oversight is a continuum that can range from low intensity, such as customer concurrence in reviews (e.g., Preliminary Design Review, Critical Design Review), to high intensity oversight, in which the customer has day-to-day involvement in the supplier's decision-making process (e.g., hardware inspections). (Definition from source document: NPR 8735.2, Management of Government Safety and Mission Assurance Surveillance Functions for NASA Contracts.)
Problem	The subject of the independent technical assessment/inspection.
Recommendation	An action identified by the assessment team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.
Reversal	The changing of the normal polarity of a cell, typically due to overdischarge of the cell.

10.0 Acronyms List

ATK	Alliant Techsystems, Inc.
CALIPSO	Cloud-Aerosol Light Detection and Ranging Instrument (LIDAR) and Infrared Pathfinder Satellite Observations Mission
COMSAT	Communications Satellite
COTS	Commercial-Off-the-Shelf
ESMD	Exploration Systems Mission Directorate
GOES	Geostationary Operational Environmental Satellite
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
JPL	Jet Propulsion Laboratory

JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LIDAR	Light Detection and Ranging Instrument
Li-Ion	Lithium-Ion
LM	Lockheed Martin
MCD	Manufacturing Control Document
MSFC	Marshall Space Flight Center
MTSO	Management and Technology Support Office
NAFBSWG	NASA Aerospace Flight Battery Systems Working Group
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
Ni-H_2	Nickel-Hydrogen
NRB	NESC Review Board
SMD	Science Mission Directorate
SOMD	Space Operations Mission Directorate
SPRT	Super Problem Resolution Team (now called Technical Discipline Team (TDT))
TAC	The Aerospace Corporation
TDRS	Tracking and Data Relay Satellite
TDT	Technical Discipline Team
V&V	Validation and Verification

Volume II: Appendix (stand-alone volume)

Appendix A. Hubble Space Telescope (HST) Nickel-Hydrogen Battery and Battery Module Handling Plan

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14. ABSTRACT
This NASA Aerospace Flight Battery Systems Working Group was chartered within the NASA Engineering and Safety Center (NESC). The Battery Working Group was tasked to complete tasks and to propose proactive work to address battery related, agency-wide issues on an annual basis. In its first year of operation, this proactive program addressed various aspects of the validation and verification of aerospace battery systems for NASA missions. Studies were performed, issues were discussed and in many cases, test programs were executed to generate recommendations and guidelines to reduce risk associated with various aspects of implementing battery technology in the aerospace industry. This document contains Part 2 - Volume I: Recommendations for Technical Requirements for Inclusion in Aerospace Battery Procurements of the program's operations.

15. SUBJECT TERMS
Aerospace; Battery; International Space Station; Light Detection and Ranging Instrument; Lithium-ion; Nickel Hydrogen

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