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NASA Aerospace Flight Battery Program

Recommendations for Technical Requirements for Inclusion in Aerospace Battery Procurements

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

Volume II: Appendix

February 18, 2010

Volume II: Appendix

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

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HUBBLE SPACE TELESCOPE (HST) NICKEL-HYDROGEN BATTERY AND BATTERY MODULE HANDLING PLAN

FLIGHT SYSTEMS & SERVICING PROJECT

SUBMITTED IN ACCORDANCE WITH REQUIREMENTS OF
GSFC CONTRACT NAS5-50000, Part C

Lockheed Martin Space Systems Company
Missiles & Space Sunnyvale Operations

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Table of Contents

LMMS/P564384

Draft Rev A
December 06, 2005

List of Figures

LMMS/P564384
Draft Rev A
November 30, 2005

1.0 Scope

The requirements described herein apply to procedures to be followed after delivery of Nickel Hydrogen (NiH_2) battery modules and the flight spare battery (FSB) from the vendor. In general comments and recommendations made specifically for the flight modules have application for the flight spare battery as well. Generally, requirements designed to minimize any conditions that could have deleterious effects on battery cell performance and life include:

- Exposure to over-charge or load surge currents and cell over-discharge (Section 3.0)
- Long periods of open-circuit stand while charged or partially charged (Section 3.0)
- Exposure to high temperatures and prolonged or uncontrolled testing (Section 3.2)
- Protection against Hydrogen poisoning (Section 6.3)

1.1 General

This document describes the plan for handling and maintenance of the NiH_2 battery modules for the Hubble Space Telescope (HST) Servicing Mission 4 (SM4), and the FSB. This plan is to be followed after delivery from the vendor. The handling and maintenance plan described herein will ensure that battery and modules perform optimally and pose minimal risk to personnel and equipment during transportation activities.

1.2 Function and Description

The NiH_2 Battery Module Orbital Replacement Unit (ORU) is intended for use as a power source for the HST. It is commonly referred to as the "module," P/N 4177918 and consists of three electrically independent, but mechanically dependent NiH_2 Batteries, P/N 4177774 (referred to as the battery). Each battery, including the FSB, consists of 22 electrically series-connected, RNH-90-3 NiH_2cells (P/N 4177758) wired to a power connector (J1), with a Battery Isolation Switch (BIS) installed at the vacant cell position (#15). Each battery has a current sensor, two independent heater circuits, two independent pressure monitoring strain-gauge circuits on two cells, a temperature monitoring circuit (RT1) and four charge control thermistors (RT2 and RT3, RT4 and RT5) wired to a sense connector (J2). Each battery has individual cell voltage sense monitoring wires to a sense connector (J3).

2.0 Applicable Documents

2.1 Government Documents

NASA Reference Publication 1314, NASA Handbook for Nickel-Hydrogen Batteries

NASA Manned Space Vehicle Battery Safety Handbook JSC 20793

KHB 1700.7 Space Shuttle Payload Ground Safety Handbook

SMR 4090 Servicing Mission Requirements, Product Assurance

FED-STD-209 Clean Room and Workstation Requirements, Controlled Environment

STE-57 HST Voltage/Temperature Improvement Kit (VIK)

STR-29 HST Servicing Mission Contamination Control Requirements

540-PG-8715.1.1 Mechanical Systems Division Safety Manual Vol. 1

NSTS 07700 Program Definitions & Requirements, Volume XIV, Space Shuttle Payload Accomodations

NSTS 1700.7b Safety Policy and Requirements for Payloads Using the STS, 5/22/96 (Change Packet No. 17, 6/14/04)

KHB1700.7 Space Shuttle Payload Ground Safety Handbook, Rev C, 8/99

NSTS/ISS 18798 Interpretations of NSTS/ISS Payload Safety Requirements, REV B, 9/1/97 (Change Packet No. 7, 10/00)

JSC 20793 Crewed Space Vehicle Battery Safety Requirements, Rev A, January 2005

EA-CWI-33 Battery Processing, January, 2005

NSTS/ISS 13830 Payload Safety Review and Data Submittal Requirements, Revision C, Change 8, 1/25/05

JSC 26943 Guidelines for the Preparation of Payload Flight Safety Data Packages and Hazard Reports, 2/17/95

2.2 LMSS Documents

LMMS/P106692	Detail Specification for the RNH-90-3 Nickel-Hydrogen Battery Cell
4177751	Detail Specification for Nickel-Hydrogen Battery Module CCA No. 3215
4177918	Battery Module, ORU Assembly
4177755	Top Assembly, Battery Module
4177758	RNH-90-3 Cell Envelope Drawing
4177774	Envelope Drawing, Nickel Hydrogen Battery
HEC-PHT-059	Packaging, Handling Transportation Record
LMMS/P508217	HST NiH_2 Battery Test Cell Handling and Storage Plan

3.0 Handling Requirements

Batteries are ESD sensitive and wrist straps are required during any physical handling. Connector caps on J1, J2 and J3 connectors must be in place for all batteries, if practical. The requirements and constraints defined herein apply to charging and conditioning of the flight NiH_2 batteries. Failure to comply with these requirements may result in degradation of battery performance and possible battery damage.

NASA Reference Publication 1314, Chapter 1, describes design features of NiH_2 cell technology. Excessive overcharge is considered the most likely condition that could result in battery cell temperatures rising beyond specified limits of LMSC/4177751. Whenever a battery cell is overcharged, all of the excess energy is dissipated as heat and the sensed cell temperature may rise rapidly. NASA Handbook JSC-20793 provides general information for safe handling, storage, assembly, and operation of NiH_2 flight cells and batteries. Thermal runaway of the batteries during integration and test charging periods is controlled by test procedures and battery charge controllers designed to limit battery overcharge temperatures and cell pressures. The maximum pressure that can be produced in an RNH-90-3 NiH_2 battery cell is limited by design to 1200 pounds per square inch (psi). Active thermal control is required to limit maximum battery cell temperatures to help control thermal runaway conditions that could develop during overcharging. Operational control of cell over-charge and over-discharge conditions is defined in Section 3.3.

Long periods of open circuit stand in the charged or partially charged state are to be avoided to ensure that maximum cell performance and life will be obtained. When batteries are not being tested, long term storage requirements defined herein shall be followed. Flight batteries and modules should be maintained fully discharged, on open circuit, and in cold storage when not in use, except as delineated in Section 3.4.4 and Section 6.3. Although the RNH-90-3 NiH_2 battery cells are designed to withstand the effects of limited room temperature discharged open circuit exposure, room temperature storage conditions should be kept to a minimum within test constraints and conditions defined herein.

Some battery storage conditions, especially conditions that form as a result of cell changes that occur as a function of life such as nickel Pre-charge loss, require additional storage precautions. Specifically, batteries that contain cells that have become hydrogen Pre-charged should be stored using active storage techniques. These techniques will eliminate, or at least limit to acceptable levels, the deleterious effects of storage of cells containing hydrogen gas. General guidelines are contained herein to determine if a battery contains hydrogen Pre-charged cells and the appropriate precautions that should be followed depending on the determined type of Pre-charge.

3.1 Battery Logbook

A logbook shall be kept in accordance with SMR 4090 for the FSB and for each flight module .

3.2 Environment

The battery REE should be contacted in the event that any limit, defined herein, is exceeded. In the event that any of these conditions cannot be met, an exception may be permitted, but only with the approval of the battery REE and the Quality Assurance Manager.

3.2.1 Contamination Control of Hardware

Handling and testing of the battery/module shall be performed in an environment with good housekeeping practice as delineated by FED-STD-209 class 100K. Clean room compatible gloves and wrist straps shall be worn at all times while handling the battery/module directly. The external surfaces of the module shall be clean to level 400B requirements.

The battery/module environment shall be controlled to preclude condensation. During testing, the battery/module temperature shall be maintained at least 2.8° C (5° F) above the dew point of the battery/module environment to prevent condensation. During storage periods, desiccant shall be used as necessary to prevent condensation on the battery/module in cool environments.

3.2.2 Temperature (Non-operational)

Battery temperatures should be maintained between -10.0° C and 25° C (14° F to 77° F) within the time constraints delineated below. Battery temperatures during Shuttle Bay operations may exceed 30° C (86° F) for no more than 72 hours total (accumulated) time, but at no time shall any battery temperature exceed 37.8° C (100° F).
Battery environment temperatures during periods of non-operation shall be monitored either by temperature monitor thermistors (RT1) and (RT2 through RT5), or by other temperature recording devices so that compliance with the following temperature constraints as defined in Sections 3.3 and 6.3 can be verified.

For Nickel Pre-charge:		
Periods less than 3 days (any SOC)	-10.0° C to 25.0° C	(14° F to 77° F)
Periods less than 3 days (Shuttle Bay Only - any SOC)	-10.0° C to 30.0° C	(14° F to 86° F)
Periods between 3 and 14 days (any SOC)	-10.0° C to 25.0° C	(14° F to 77° F)
Periods between 14 and 28 days (requires letdown)	-10.0° C to 22.2° C	(14° F to 72° F)
Periods greater than 28 days (requires letdown)	-5.0° C to 5.0° C	(23° F to 41° F)
For Hydrogen Pre-charge (requires active storage):		
Periods less than 3 days (any SOC)	-10.0° C to 25.0° C	(14° F to 77° F)
Periods less than 3 days (Shuttle Bay Only - any SOC)	-10.0° C to 25.0° C	(14° F to 77° F)

Periods between 3 and 14 days	-10.0° C to 25.0° C	(14° F to 77° F)
Periods between 14 and 28 days	-10.0° C to 22.2° C	(14° F to 72° F)
Periods greater than 28 days	-5.0° C to 5.0° C	(23° F to 41° F)

3.2.3 Temperature (Operational)

The battery temperature during electrical operation (charging, discharging, conditioning, *etc.*) shall be maintained as per Section 3.3.1.

3.3 Battery Operational Limits

Battery operation shall be in accordance with the limits summary contained in Appendix A and the flow diagrams contained in Appendix B. During battery operation temperature, voltage, current, and battery strain gauge pressure will be continuously monitored using the following electrical sense circuits and comparing their output to the tables and graphs in Appendix C:

a. Temperature Monitor Thermistor (RT1) Appendix C-1
Requires 28 ± 4 V. input; Output is 0 to 5 V

b. Thermistors (RT2 and RT3, RT4 and RT5) Appendix C-2

c. Current sensor Appendix C-3
Requires 28 ± 4 V. input; Output is 0 to 5 V

d. Pressure monitors Appendix C-4
Requires 28 ± 4 V. input; Output is 1 to 5 V

Limits on temperature, current, voltage and pressure shall be as defined in the following sections.

3.3.1 Temperature (the highest value as monitored at all battery temperature monitors, RT1 through RT5)

Active thermal control will be required to limit temperature gradients across the mounting surface for the battery module to less than 2.8° C (5.0° F) across each battery as determined by the battery temperature monitors.

Battery Charging (constant current)	-10.0° C to 22.2° C	(14° F to 72° F)
Battery Charging (pulse as in Section 6.1.2)	-10.0° C to 25.0° C	(14° F to 77° F)
Battery Discharging	-10.0° C to 25.0° C	(14° F to 77° F)
Battery Letdown	-10.0° C to 25.0° C	(14° F to 77° F)
Trickle Charging	-10.0° C to 22.2° C	(14° F to 72° F)
Battery Reconditioning	-10.0° C to 22.2° C	(14° F to 72° F)

NOTE: Temperature excursions during charge to 25.0° C (77° F) and during discharge to 30.0° C (86° F) are allowed, as per Sections 6.1.1 and 6.2.1, respectively.

3.3.2 Current

The following current limits shall be observed for the battery at all times:

Charging:
Conventional 4.0 to 30.0 A
Trickle (6.1.4) 0.4 to 1.4 A
Discharging:
Battery voltage > 26.4V 0.0 to 20.0A (30A peak for 10 seconds max)
Battery voltage ≥ 22 V 0.0 to 20.0 A

Battery voltage < 22 V   0.0 to 5.0 A

Battery discharge shall never be initiated if the battery voltage is below 22.0 V except when discharging individual cells through resistive loads applied to the J3 connector to a battery terminal voltage and/or as per Section 6.2.1. Full rate discharge shall never be initiated if a battery cell pressure is below 100 psi, as determined from the battery cell strain gauges (as monitored through the J2 connector).

3.3.3 Voltage

The following voltage limits should be observed for the battery during system testing:

Voltage upper limit:	VT limit Appendix A-2) or 34.3 V, whichever is **lower**
Voltage lower limit:	22.0 V except for letdown, as per Section 6.2.3

If a battery voltage above the upper limit or below the lower limit is observed during system testing, any electrical activity being performed on the battery (*e.g.* charge or discharge) shall be terminated immediately. The Battery REE shall be consulted before continuation of electrical activity.

3.3.4 Pressure

The following pressure limits shall be observed for the battery during system testing:

Pressure upper limit:	1200 psi
Pressure lower limit:	0 psi

If any battery cell strain gauge indicates that a cell pressure exceeds 1200 psi or falls to the lower 0 psi limit, all electrical activity being performed on the battery (*e.g.* charge or discharge) shall be terminated immediately, except during battery letdown per Section 6.2.3. The Battery REE shall be consulted before continuation of electrical activity.

3.4 Transportation and Mechanical Handling

3.4.1 Delivery from Vendor

After battery module acceptance testing and inspections are completed at the subcontractor, the batteries will be discharged and letdown to procedures specified in Section 6.2.3 as applicable. The modules are to be placed in protective packages for shipment in accordance with requirements of HEC-PHT-059. The modules will be delivered with batteries in the fully discharged and open-circuit state (as described in Section 6.3.2).

3.4.2 Transportation

Transportation activities shall be per pre-approved P442 Handling Procedures (reference HEC-PHT-059). Modules shall be moved with protective packaging to prevent mechanical damage, and the BIS shall be in the open position. During transportation, batteries should be fully discharged and letdown, as described in Section 6.2.3. If, however, battery modules are to be transported in the charged open circuit condition, all connectors on the batteries shall be capped. Whenever the module is to be shipped, shock, temperature, and humidity indicators shall be used to monitor the conditions to which the module has been subjected.

3.4.3 Handling Upon Initial Receipt At GSFC

As soon as possible after incoming inspection, battery/modules shall be placed in controlled storage unless required for further processing within 14 days. The incoming shipping container may be used as protective packaging for cold storage or the battery/module may be double bagged and N2 purged. Desiccant bags shall be used as necessary to prevent condensation on battery/module surfaces.

A brief description of some of the GSE required, its purpose and availability is contained in Appendix D.

3.4.4 Movement and Installation

If charged batteries are to be physically handled, **each BIS must be in the OPEN position**, which provides electrical isolation safety for J1 and J2 connectors. J3 is not included in the BIS functionality and shall therefore be capped.

Flight module batteries shall be fully discharged and letdown during all operations in which the modules are physically handled, **unless program operations require batteries to be charged**. Operations include removal of modules from shipping containers, transfer to the carrier assembly area, and mechanical and electrical GSE installation to the carrier. Definition of electrical installation shall also include mating and de-mating operations. The flight module battery discharge and letdown shall be performed using the procedures given in Section 6.2.3.

3.4.5 Transportation to Launch Site

The flight modules are to be transported to the launch site installed in shipping containers maintained within temperature limits delineated in Section 3.2.2. If necessary, the module may be transported separately from the carrier. Ideally, the flight module batteries would be discharged and letdown using the procedures given in Section 6.2.3. If, however, the batteries are to be shipped other than in a letdown condition, then battery charge using the appropriate procedure given in Section 6.1 should be performed.

3.5 Battery Rework

Battery rework, either at the current location, or at Eagle Picher, maybe required, which possibly could include cell replacement of weak capacity cells, and/or strain gauge electronic trouble shooting and replacement.

3.5.1 Battery Rework of Nickel Pre-charged Cells

All procedures for handling and transportation detailed above (Section 3.4) apply to batteries which are judged to be nickel pre-charge.

3.5.2 Battery Rework of Hydrogen Pre-charged Cells

Procedures for battery rework for batteries, which are judged as being hydrogen pre-charge, are made more difficult due to the need to keep the batteries charged using active storage, except when absolutely required for safety reasons. When hydrogen pre-charge batteries require rework, a special handling procedure will be developed by the battery REE and the manufacturer, Eagle Picher, to address the special circumstances of the work required, the transportation issues, and the handling precautions that are required for the rework, and the safety of personnel.

4.0 Post Transportation Tests (Maintenance)

All operations shall be subject to monitoring and validation by Quality Control (QC). Validation shall be indicated on all data sheets and flow records by the signature or stamp of an authorized QC representative. These tests shall be performed upon receipt at GSFC and KSC and, at the discretion of the REE, may be performed after any event that might have compromised the integrity of a battery.

Some tests described in this section are not appropriate for verification of a battery that has not been discharged as described in Section 6.2.1. Exceptions or modifications to these tests are noted in the test procedures.

4.1 Electrical Equipment Check-Out

Prior to any stand alone electrical testing on any of the flight modules (including the Flight Spare Battery), the functionality of the test equipment shall be verified. Protection shall be provided such that the nominal 28 V excitation voltages applied to the telemetry and heater circuits do not exceed 32 V (GSE).

4.2 Battery Functional Testing

Each battery may, at the discretion of the Battery REE, be subjected to the following tests to demonstrate conformance with the requirements of the Battery Module Specification (4177751. The relevant battery module specification paragraph is provided with each required test.

4.2.1 Electrical Continuity (Paragraph 3.2.1.1.11)
4.2.2 Isolation Resistance (Paragraph 3.2.1.1.12)
4.2.3 Thermistor (Paragraph 3.2.5)
4.2.4 Temperature Monitor (Paragraph 3.2.3)
4.2.5 Current Monitor (Paragraph 3.2.4)
4.2.6 Heater Status Monitors (Paragraphs 3.6.3.3 and 3.6.3.4)
4.2.7 Strain Gauge Circuitry (Paragraph 3.2.10)

5.0 Preparation of Modules for Use and/or Shipment

The requirements listed herein shall apply to the FSB and flight modules including the flight module battery thermal environment and test conditions. Any charging, discharging and other electrical functions shall be in accordance with this plan.

5.1 Preparation of Modules for Use

5.1.1 Unpacking and Verification Procedures

Procedures for unpacking are delineated in HEC-PHT-059.

5.1.2 Functional Bench Checks

If battery is in a discharged state, as received, perform electrical checks of the module, defined in Section 4.2, to verify wiring integrity as directed by battery REE.

5.1.3 Removal From Cold Storage

Upon removal from cold storage, the battery/module shall be placed in a room temperature environment for warm-up. The battery/module shall be grounded for ESD protection and a dry Nitrogen purge shall be maintained at the rate of 4 standard cubic feet per hour for 48 hours. At the completion of the 48 hour warm-up period on Nitrogen purge, battery/module protective bagging may be removed.

5.1.4 Module Maintenance

Perform battery maintenance per Section 6.0 as required by program needs.

5.2 Preparation of Modules for Shipment

The sequence of operations is delineated by GSFC P442 Procedure, reference HEC-PHT-059 , Packaging, Handling Transportation Record.

If charged batteries are to be physically handled, **each BIS must be in the OPEN position**, which provides electrical isolation safety for J1 and J2 connectors. J3 is not included in the BIS functionality and shall therefore be capped.

Key operations are:

- Placing the Transportation Adapter Plates (TAPS) onto the handling dollies
- Lowering the TAP/module into the container.
- Installing instrument assemblies.

6.0 Battery Maintenance Operations

The following section describes the generic battery maintenance operations required after delivery of batteries to maintain a desired battery State-of-Charge (SOC). These operations include charge, discharge, resistor letdown, and reconditioning operations performed on individual batteries.

Proper handling and charge control of NiH2 batteries is very critical for HST because the battery capacity is limited by thermal considerations, both during charge, and during open circuit storage (OCV) periods, such as when the HST batteries are sitting at OCV during pre-launch and post launch periods. Figure 6-1 details the capacity loss (self discharge) after open circuit stand over a period of four weeks. Note that after only 10 days at 77°F the battery has lost approximately 50% of its starting capacity. This can have a critical impact upon battery handling and charge maintenance prior to launch, if batteries are to be delivered at the required SOC, at the time of the Servicing Mission.

Figure 6-1. Typical Nickel-Hydrogen Battery Open Circuit Capacity Loss (TBR)

6.1 Battery Charging

6.1.1 Charging a Fully Discharged Battery

Figure 6-2 details the voltage and current profile for a typical charge profile of a discharged battery, which is the basis of charge procedures described below. Note the typical voltage rollover, the current decrease in steps for VT considerations, and the higher voltage obtained, with the optional pulse charging, at the end of the high rate (C/20) charge profile versus constant current trickle charging at 0.6 A (C/150) around 7 hours elapsed time. Figure 6-3 further details the current, temperature, and capacity converted from strain gauge readings, for the same profile. It should also be noted that lower full charge rates may be used for initial charge of a discharged battery, if higher charge rates can not be supported by the charging power supplies. The charge efficiencies will be less and charging times will be longer, but the same end of charge procedures described below may be used.

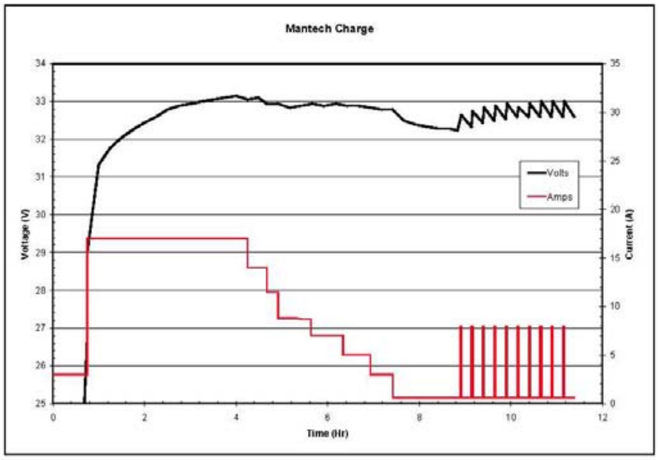


Figure 6-2. Typical Mantech Charge Profile, With Voltage Rollover and Pulse Charging

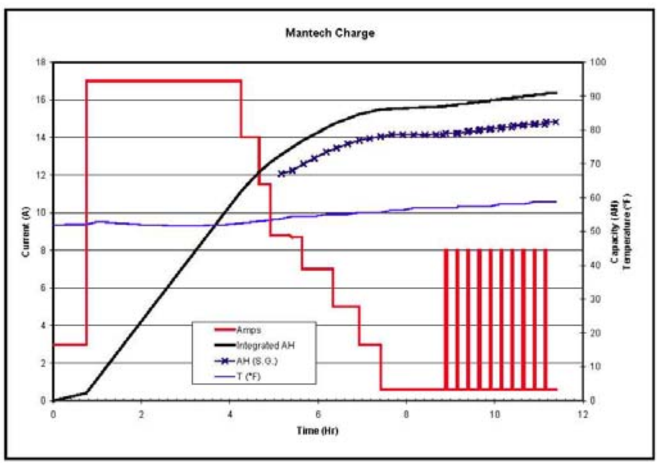


Figure 6-3. Typical Mantech Charge Profile Detailing Capacity and Temperature

Battery conditioning, optimally defined by Section 6.4.1, shall be performed on a battery that has been fully discharged with cell letdown per Section 6.2.1, Step 3b. Battery charging shall be conducted within the limits specified in Section 3.3. Figures 6-2 and 6-3 illustrate an example of a high rate charge profile where active thermal control was required to limit maximum battery cell temperatures to help control thermal runaway conditions that can develop during overcharging at temperatures from 10.0° C to 15.0° C (50° F to 59° F).

External cooling equipment, such as fans, or conditioned air or missile grade air or dry nitrogen gas, should be used as necessary to keep the battery cool. Care should be taken to ensure that the temperature remains at least 2.8° C (5° F) above the dew point of the battery environment to prevent condensation per Section 3.2.1.

Note that desired battery temperatures for initiation of charge are -2.2 ± 2.2° C (28 ± 4° F) for 32° F standard capacity and 4.4 ± 2.2° C (40 ± 4° F) for 50° F standard capacity comparisons with Module ATP data. Any battery that has been fully discharged (Section 6.2.1, Step 3a) may also be charged per the following procedure:

1. Ensure that external cooling equipment is on and functioning such that battery temperature is within a range from -10.0° C to 22.2° C (16° F to 72° F). Note that a temperature of 4.4 ± 2.2° C (40 ± 4° F) is specified during the initial Module ATP conditioning charge at 9.3 amps. The temperature is then lowered to –2.2 ± 2.2° C (28 ± 4° F) during final conditioning charge at 4.0 amps. If capacity trend data is desired, then battery temperatures should be controlled accordingly for comparison to 50° F standard capacity data generated during Module ATP. Otherwise, charge per the following steps.

2. Charge at 9.3 ± 0.2 A constant current to a Peak Voltage within the VT limits of Appendix A-2, or until battery voltage reaches 34.3 V or until battery temperature reaches 22.2° C (72° F), but for no longer than 10.0±0.1 hours. If the battery temperature reaches 22.2° C (72° F), charging shall be stopped until battery temperature drops below 20.0° C (68° F), and then charging per Step 3 shall be started.

3. Charge at 4.0 ± 0.2 A constant current for 14.0 ±0.1 hours, or until the battery voltage reaches the VT limits of Appendix A-2 or reaches 34.3 V. Note that battery temperature might begin to increase around 33.0 ± 0.2 V, and charging should be stopped if the temperature reaches 22.2° C (72° F). The battery temperature might continue to rise and an excursion to 25.0° C (77° F) is allowed per Section 3.3.1, but charging per Step 4 shall not be started until battery temperature drops below 20.0° C (68° F).

4. Pulse charging, detailed in Section 6.1.2 and Figure 6-4, may be used to increase battery SOC without appreciably increasing battery thermal dissipation.

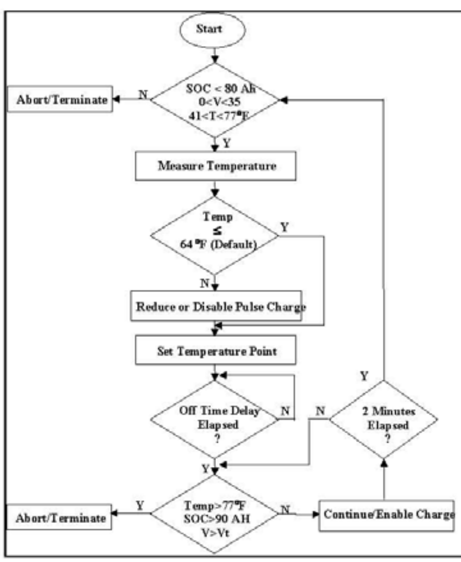
A battery is considered to have achieved full charge after charging within thermal constraints and conditions defined herein. A full state of charge may be maintained by trickle charging at a rate of 0.9 A ± 0.5 A, or as defined in Section 6.1.2.

6.1.2 Pulse Charging

Acceptable pulse charge regimes are illustrated in Figure 6-2. Of these, the preferred regime is:

8.0 ± 2.0 A	2.0 ± 0.1 minutes
0.6 ± 0.2 A	13.0 ± 0.1 minutes

Maintain environment at -10.0° C to 22.2° C (14° F to 72° F) and ≥ 2.8 C° (5F°) above the dew point to prevent condensation. Missile grade air or dry nitrogen may be used to reduce the dew point.



Temperature °F	Temperature °C	Off Time (Minutes)	Vt (Volts)
64	17.8	0.0	32.19
65	18.3	0.3	32.16
66	18.9	0.5	32.11
67	19.4	1.0	32.09
68	20.0	2.0	32.06
69	20.6	4.0	32.04
70	21.1	5.5	32.01
71	21.7	8.0	31.99
72	22.2	10.0	31.96
73	22.8	13.0	31.91
74	23.4	18.0	31.89
75	23.9	28.0	31.86
76	24.4	58.0	31.84
77	25.0	**Abort Charging**	

Figure 6-4 Charge Flow Diagram with 8 Amp Pulse

6.1.3 Battery Top-Off Charge

At conclusion of any system test, the flight module open-circuit battery voltages shall be measured within 10 to 15 minutes of charge termination and those voltages shall be recorded in the logbook, as required in Section 3.1.

6.1.3.1 Battery open-circuit voltage is less than 29.5 V but greater than 28.6 V

A recent test may have left the battery at less than 75% SOC, and cause for this SOC needs to be determined before proceeding. If any battery open-circuit voltage is less than 29.5 V but not less than 28.6 V, the battery shall be recharged before any new test or activity.

The following procedure shall be used to apply a Top-Off Charge to the partially discharged battery:

1. Ensure that external cooling equipment is on and functioning such that battery temperature is maintained within the range of -10.0° C to 22.2° C (14° F to 72° F).

2. Charge at 9.3 ± 0.2 A constant current to a Peak Voltage within the VT limits of Appendix A-2 or until the battery voltage reaches 34.3 V, whichever comes first. If the battery temperature during charge exceeds 22.2° C (72° F), charging shall be stopped until the temperature drops below 20.0° C (68°F). Pulse charging may then be initiated.

3. Pulse charging, detailed in 6.1.2 and Figure 6-4, may be used to limit battery thermal dissipation and maximize the SOC of the battery.

4. At conclusion of charge at 9.3 ± 0.2 A or pulse charging, the charge rate may be reduced to a trickle rate of 0.9 ± 0.5 A after the battery temperature drops below 20.0° C (68°F). If the temperature during trickle charge exceeds 22.2° C (72° F), charging shall be stopped until the temperature drops below 20.0° C (68°F) and charge may be resumed at the direction of the Battery REE.

This method of charging the battery relies upon recognition of the maximum attained battery voltage during charging. An example of Peak Voltage and "roll over" from a high rate charge profile is shown in Figure 6.2. At a temperature of 10.0° C (50° F) and constant charge rate of 9.3 A, the battery voltage may reach a thermal limit around 33.0 ± 0.2 V and require charge termination. If battery temperature reaches 25.0° C (77° F) after any charge termination, notify the Battery REE to review battery charge data before continuing.

6.1.3.2 Battery open-circuit voltage is less than or equal to 28.6 V

An open-circuit voltage less than 28.6 V may indicate the battery is at a low state of charge. Notify the REE to determine cause. At the discretion of the REE corrective actions could include: Discharging and then Charging (per Sections 6.2.1 and 6.1.1, respectively), or Top-Off Charging (per Section 6.1.3.1).

6.1.4 Trickle Charging

Trickle charge is the conventional method of maintaining a fully charged flight battery or module when it is not being used for testing or end item use. Trickle charge is indicated for planned periods of non-use within temperature constraints of Section 3.2.2, and is required for maintaining the battery at a full state of charge in readiness for launch after charging in accordance with Sections 6.1.1, 6.1.2 or 6.1.3.

Trickle charge is a constant charge rate of 0.9 ± 0.5 A applied to the flight battery or module at all times. Trickle charge shall be terminated if the battery temperature rises above 22.2° C (72° F), and may be resumed when temperature drops below 20.0° C (68° F). At the discretion of the Battery REE, pulse charging, as per Section 6.1.2, may be used in lieu of trickle charging, especially as the battery temperature approaches 22.2° C (72° F). External cooling equipment such as cold plates, fans or conditioned air shall be used as necessary to keep the battery cool. Whenever a battery cell is overcharged, all of the excess energy is dissipated as heat and the sensed cell temperature may rise rapidly as described herein. Active thermal control is required to limit maximum battery cell temperatures during overcharging

6.2 Battery Discharge

In addition to the constraints of Sections 3.3.1 and 3.3.2, discharge during any ground test or reconditioning operation shall be terminated if, at any time during discharge, any battery temperature reaches 25.0° C (77° F); discharge may be resumed when the temperature drops below 22.2° C (72° F). External cooling equipment, such as fans or conditioned air or missile grade air or dry nitrogen gas, should be used as necessary to keep the battery cool. Care should be taken to ensure that the temperature remains at least 2.8° C (5° F) above the dew point of the battery environment to prevent condensation per Section 3.2.1.

The complete and uninterrupted discharge procedure can take up to 24 hours or more for a fully charged battery to letdown all battery cells per Section 6.2.1, Step 3b, for storage periods greater than 14 days per Section 3.2.2. The battery may be fully discharged per Section 6.2.1, Step 3a, for periods less than 14 days per Section 3.2.2.

6.2.1 Discharge Procedure

The following procedure shall be used to fully discharge the battery and/or to letdown for nickel pre-charge determination or for full letdown for storage:

1. Connect the GSE resistor letdown circuit to each battery's J3 sense connector to monitor all cell voltages. Ensure that external cooling equipment is on and functioning such that battery temperature is maintained within the range of -10.0° C to 25.0° C (14° F to 77° F) except as specified in Section 6.4.1.

2. Discharge at 15.0 ± 0.2 A constant current until the battery voltage reaches 22.0 V, or any cell voltage reaches 0.9 V. Record capacity (Ah) when battery terminal voltage reaches 26.4 V. Note: If desired, the rate may then be reduced to 5.0 ± 0.2 A constant current until the battery voltage reaches 20.0 V, or any cell voltage reaches 0.6 V, and then 3.0 ± 0.2 A constant current until the battery voltage reaches 15.0 V, or any cell voltage reaches 0.6 V. If the temperature during the discharge exceeds 25.0° C (77° F), discharging shall be stopped. Even when discharge is discontinued as the temperature reaches 25.0° C (77° F), the temperature might continue to rise to 30.0° C (86° F) per Section 3.3.1. Discharge may be resumed when battery temperature drops below 22.2° C (72° F).

3. Continue to discharge the battery, through the GSE resistor letdown circuit across J3, until the battery voltage reaches:

   a. Full Discharge: 11.0 V if the battery is to be reconditioned for recharge within 14 days
   b. Cell letdown for nickel pre-charge determination: All cell voltages are below 0.10 +0.00 -0.10 V.,
   c. Cell Letdown: All cell voltages are below 0.01 + 0.00 -0.01 V, for 24 hours minimum, and remain below 0.5 V after 24 hours open circuit voltage recovery if battery is to be stored for ≥14 days.

6.2.2 Battery Discharge Capacity

The capacity of the battery recorded from the discharge operation shall be that measured from Step 2 of the discharge procedure in Section 6.2.1 (15 A discharge to battery voltage = 22.0 V). The capacity of the battery is defined by the time to reach 26.4 V, and is dependent upon its temperature. After operating or charging at higher temperatures, the Ah capacity of the battery may be lower than at lower temperatures.

6.2.3 Battery Letdown

Prior to transportation, mechanical installation or mechanical handling operation, the battery shall be letdown, except where program operations require a charged battery as allowed in 3.4.2 and 3.4.4. For battery letdown, the battery shall be discharged according to Steps 1, 2 and 3 in Section 6.2.1. The purpose of cell letdown is to discharge all hydrogen gas in the cells to ensure that hydrogen poisoning cannot occur during any discharged open circuit storage period.

6.3 Non-Operational Periods and Storage

Non-operational is defined in Section 7.1.

6.3.1 Charged Non-Operational

The FSB and flight module batteries may remain non-operational, open-circuit charged within the temperature and time constraints of Section 3.2.2. Such periods shall be initiated after the battery cells have been fully charged. For periods of no electrical activity longer than 7 days, depending on SOC, a topping charge or discharged open-circuit storage shall be used unless otherwise approved by the REE. For periods up to 28days, as may be encountered during integration and test at GSFC or KSC storage temperatures should be maintained per section 3.2. Trickle charge or discharged open-circuit storage, depending on the determined type of Pre-charge, is always preferable to an open-circuit charged condition. Voltage and temperature shall be monitored and recorded daily during any charged, open-circuit period unless otherwise concurred with by the REE per Section 6.1.3.2.

6.3.1.1 Charge To Restore Full SOC Following a Open-Circuit, Charged, Non-Operational Periods

During periods of open-circuit charged non-operation, the battery self-discharges at rates which, over a period of time, can lead to significant depths-of-discharge. To calculate the capacity loss the following Arrhenius Equation may be used to estimate loss as a function of time and temperature.

For OCV periods at variable temperatures, the absolute capacity, C(t), remaining at time t, is given by the Arrhenius equation;

$$\mathbf{C(t) = C(to) * exp\ [-k(t - to)]}$$

Where C(to) is the absolute capacity at the beginning of the time period, (t – to), k is given by the equation

$$\mathbf{k = 354.9\ exp\ (-3510 / T)}$$

with k in hr^{-1}, T in °K, and t is in hours.

6.3.2 Pre-charge Testing Condition

If the battery has been stored with nickel pre-charge, i.e., non-active, a go/no go Pre-charge test may be performed each time the battery is removed and replaced in extended storage if the period of time from the last Pre-charge test is beyond 3 months, to determine pro-charge condition. One of the following go/no go Pre-charge tests shall be performed at the discretion of the battery REE:

Voltage Recovery after Letdown

1. Ensure that all cells in the battery have been let down to below 0.1V per section 6.2.1.
2. Place the battery on open circuit at room temperature for 24 hrs.
3. Battery REE will make a determination based on residual voltages what the Pre-charge type is for each cell.
    a. Nickel pre-charge signature is cell voltage below 0.6 V
    b. Hydrogen pre-charge signature is cell voltage above 0.6 V

Cell Voltage and Pressure will be measured. Cell Voltages should be below 0.6V (TBR) and Cell Pressures should be below 15 psi (TBR). Based on Cell Voltage readings, the REE will make a determination as to the pre-charge type for each cell.

Reversal Response

1. Ensure that all cells in the battery have been letdown to below 0.01V per section 6.2.1.
2. Using a power supply, discharge the battery for 5 minutes at C/40 while recording all cell voltage data frequently (every 30 seconds or less). This step will cause the cells to go into "reversal" producing a negative voltage.

3. Charge the battery for 20 minutes at C/50 or until all cell voltages are above 1.30V.
4. Letdown all cells in the battery to below 0.01V per section 6.2.1.
5. Battery REE will make a determination based on reversal and charge voltages what the precharge type is for each cell. A Nickel pre-charge cell will have a voltage, during reversal, of < -0.5 V (typically < -1.500 V) while a Hydrogen pre-charge cell will have a voltage of > -0.5 V. (typically ~ -0.100 V).

If any or all cells in the battery/module are determined to be Hydrogen pre-charged (i.e. contain hydrogen gas at the end of the letdown) or have marginal precharge proceed to active storage per section 6.3.6. If all cells are determined to be Nickel pre-charged initiate the appropriate storage procedure per section 6.3.3, 6.3.4 or 6.3.5

6.3.3 Storage Less than 28 Days (Nickel Pre-charged Cells)

The battery may be stored in the discharged open-circuit condition per Section 6.2.3 for short times at room temperature within the limits defined in Section 3.2.2, which limits discharged open-circuit storage to periods of less than 28 days.

6.3.4 Storage Greater than 28 Days – Cold Storage (Nickel Pre-charged Cells)

If the discharged battery is not intended to experience any electrical activity for a period of 28 days or more, it shall be letdown and placed in refrigerated storage at –5.0° C (23° F) to +5.0° C (41° F).

6.3.5 Extended Cold Storage (Nickel Pre-charged Cells) Conditioning

When the duration from the last electrical activity on a battery in cold storage approaches 365 days, or at battery REE direction, the battery shall be removed from cold storage for conditioning cycles per 6.4.1 and Pre-charge testing per 6.3.2 if previous testing did not indicate Hydrogen Pre-charge. After the successful completion of all testing and data review, the battery shall be placed back into cold storage.

6.3.6 Active Storage (Nickel or Hydrogen Pre-charged Cells)

Long-term storage of batteries at room temperature (for 28 days or more) is not recommended. Whenever partially charged batteries are expected to remain inactive for a period exceeding 5 days, it is recommended that they be charged every fourth or fifth day using the following procedure:

1. Charge per section 6.1 while observing the precautions of section 3.3 until 70% of expected full charge is reached.
2. Use one of the following active storage methods based on practicality and REE discretion:
   - Periodic top charge per section 6.1.3.
   - Continuous trickle charge per section 6.1.4.

Capacity and battery health tests shall be performed at 6 month intervals or at the discretion of the battery REE during the active storage period. Periods of time may be necessary where the batteries are required to be fully letdown, such as mating/de-mating, safety/transportation, etc. These periods of time are acceptable but should conform to the storage conditions outlined in section 3.2.2 (especially when dealing with hydrogen Pre-charged cells). Extended durations at storage conditions outside of these recommendations will likely result in hydrogen poisoning and capacity loss. Active storage should be resumed immediately after any required letdown of a battery containing hydrogen Pre-charged cells.

6.4 Battery Conditioning and Reconditioning

6.4.1 Conditioning

Battery conditioning is performed when the battery has been exposed to long duration (greater than 14 days) discharged, drained and open circuit storage at either low temperature or room temperature conditions as in Section 3.2.2. Conditioning is intended to re-establish the hydrogen gas paths within the cell and to mitigate the effects from long duration drained, open circuit storage. Battery conditioning consists of the following:

Charging:	With the cold plate at –2.2 ± 2.2° C (28 ± 4° F). Section 6.1.1, Step 2, set the cold plate to –8.9 ± 2.2° C (16 ± 4°F) and proceed immediately (*i.e.* without waiting for the cold plate to reach its set point) to Section 6.1.1, Step 3.
Open circuit	1.0 ± 0.1 hours with the cold plate at –8.9 ± 2.2° C (16 ± 4°F)
Discharging:	With the Cold plate at –8.9 ± 2.2° C (16 ± 4°F), discharge per Section 6.2.1, Step 2, and record capacity (Ah) when battery terminal voltage reaches 26.4 V.
Letdown:	With the Cold plate at –2.2 ± 2.2° C (28 ± 4° F), Section 6.2.1, Step 3a

These steps are repeated until one to five discharge sequences (at the discretion of the REE) have been achieved per Section 6.2.1, Step 2, and finally, the charging step described above is carried out to leave the battery in a full state of charge, at which time pulse charging per Section 6.1.2 may proceed at REE discretion.

6.4.2 Reconditioning.

Battery reconditioning is performed when the battery has been exposed to various charge/discharge operations and the battery state-of-charge cannot be accurately determined. It shall be performed whenever the battery will be subjected to a performance test (or test sequence) that will measure battery capacity and compare the test result to a specification requirement. Reconditioning is intended to balance the cells within the battery and minimize the effects of cell divergence. It will render the battery fully charged, with balanced cells, and ready for battery/module level capacity verification testing.

6.4.2.1 The battery shall be reconditioned at the following times:

- Following removal of the battery from refrigerated storage for over two weeks
- Within 28 days prior to final installation of the battery onto the carrier
- Every 28 days after end of electrical activities, other than trickle charging or storage as defined herein
- As directed by REE

6.4.2.2 Reconditioning Procedure

The following procedure shall be followed for reconditioning the battery. If the battery is known to be fully or partially charged (*i.e.* ≥ 22 V), reconditioning should begin at Step 2.

1. Section 6.1.1 (Steps 1, 2 and 3)
2. Section 6.2.1 (Steps 1, 2 and 3a)
3. Repeat Steps 1 and 2 once more
4. Section 6.1.1 (Steps 1, 2 and 3, and 4 at REE discretion)

Within the limits of Section 3.3.1, the battery should be kept as cool as possible to maximize the effectiveness of the reconditioning procedure.

6.4.3 Battery Capacity from Reconditioning

The capacity of the battery recorded from the reconditioning operation shall be that measured from the second performance of Step 2 of the reconditioning procedure in Section 6.4.2 (*i.e.* second 15 A discharge capacity measurement to 26.4 V).

6.5 Battery Reconditioning and Charging at the Launch Pad.

Battery reconditioning and charging at the launch pad will be performed with the batteries installed on the Super-Lightweight Interchangeable Carrier (SLIC). Cooling is provided by the Battery Plate Assembly (BPA) and associated vortex coolers which are integrated onto the SLIC. Reconditioning and charging will be performed to accommodate the cooling limitations of the BPA. The batteries will have been reconditioned within 28 days prior to transportation to the launch pad, with the batteries in an active storage condition when they arrive at the pad.

6.5.1 Battery Reconditioning at the Launch Pad

The batteries may be reconditioned upon arrival at the launch pad at the discretion of the REE. Reconditioning at the Pad may consist of up to two charge and letdown cycles similar to section 6.4.2.2.

The Reconditioning charge cycles shall be performed per Section 6.5.2, with the exception that the Trickle Charge and Cooling Phases may be deleted at the discretion of the REE.

Reconditioning letdown of the battery shall be performed with the cooling system regulated to maintain approximately 15° C. Discharge current shall be limited to 6 A down to 22 V to avoid exceeding the cooling capacity of the BPA. Below 22 V, individual cells shall be drained to approximately 100 mV through the GSE resistor letdown circuit across the J3 connector.

6.5.2 Battery Charging at the Launch Pad

The following pad charging profile shall be used to accommodate the cooling limitations of the BPA.

Initial Conditions: Regulate cooling to stabilize battery (Rt Ave.) at approximately 15° C (59°F) (Initial Temperature).

High-Rate Charge: Charge at 9.3 A until any battery Rt = Initial plus 2° C (18°C (64.4°F)) with maximum cooling; then step to Low-Rate Charge. Do not exceed for 10 hours.

Low-Rate Charge: Charge at 4 A until any battery Rt = Initial plus 4° C (20°C (68°F)) with maximum cooling; then step to Trickle Charge.

Trickle Charge: Charge at 0.9 A for 10 hours with maximum cooling, with the goal of achieving battery (Rt Ave.) at the initial Temperature (15°C (59°F)); then step to Cooling Phase.

Cooling Phase: Terminate charge and regulate cooling to maintain battery (Rt Ave.) at the initial Temperature (15°C (59°F)) for 36 hours; then terminate cooling.

For the final charge cycle, battery disconnects and launch closeout activities will commence after completion of the Cooling Phase.

7.0 Notes

7.1 Terminology

Letdown	A final step in a full battery discharge that takes the battery voltage to the lowest state that assures minimum state of charge without the risk of any cell reversal. Requires completion of Section 6.2.1, Step 3b; this is important for storage so that all cells remain below 0.5 V after 24 hours open circuit voltage recovery.
Open Circuit (OCV)	The state of a cell, battery or battery module that precludes the passage of measurable current in either direction. This is achieved by completely disconnecting the terminals of the cell, battery or module, respectively. The BIS in the OPEN position puts a battery in the open circuit state. Open circuit is effectively achieved if the terminals are connected to a device of such high impedance that no measurable current is passed.
Operational / Non-operational	A situation in which current flows through the battery or any of its cells in either direction. Non-operational implies that no current flows through the battery or any of its cells.
Room Temperature	15.0° C to 25.0° C (59° F to 77° F)
Storage	A condition such that current *cannot* be passed because the battery terminals have been disconnected by opening the BIS. The conditions of storage are described in Section 6.3.2. Temperature monitoring of environmental storage conditions is required during storage, but voltage or current monitoring is not.
Temperature Soak	Battery temperature shall be –2.2 ± 2.2° C (28 ± 4° F). The cold-plate temperatures shall be set at –2.2 ± 2.2° C (28 ± 4° F). The modules shall be allowed to soak in this environment for 12 hours, minimum. During this time the battery temperature monitors RT1, RT2, RT3, RT4, and RT5 shall be monitored for each of the batteries.
Nickel Pre-charge	State in which a fully discharged cell contains no remaining hydrogen gas and the Nickel electrodes still contain some electrochemically active charge that could be discharged if there were more hydrogen available. (Zimmerman)
Hydrogen Pre-charge	State in which a fully discharged cell contains no remaining active capacity in the Nickel electrodes. In this condition, Hydrogen gas remains within the fully discharged cell. (Zimmerman)
Hydrogen Poisoning	Loss of usable capacity above 1.2 V/cell due to second plateau formation.

7.2 Acronyms

BIS	Battery Isolation Switch
BPA	Battery Plate Assembly
DACS	Data Acquisition Control System
EMC	Electromagnetic Control
ESD	Electrostatic Discharge
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
KSC	Kennedy Space Center
ORU	Orbital Replacement Unit
REE	Responsible Equipment Engineer
SOC	State of Charge

SLIC	Super-Lightweight Interchangeable Carrier
SM4	Servicing Mission Four
STS	Space Transportation System (Shuttle)
TAP	Transport Adaptor Plate

LMMS/P564384
Baseline
October 24, 2002

APPENDIX A
BATTERY OPERATIONAL LIMITS SUMMARY

Battery Condition	Temp Rqmts[1]	Current Rqmts	Voltage Rqmts	Press Rqmts	Comments
Let Down	-10.0° C to 25.0° C (14° F to 77° F)	4.0 to 5.0 A	< 22 V	≥ 0 psi	Individual cell should be < 0.5VDC (Para 6.2.1.3 of Handling Plan)
Discharging	" "	0.0 to 30.0 A	≥ 22 V or any cell voltage reaches 0.9 V; If desired ≥ 11 V	≥ 100 psi	25°C terminates discharging while temp may rise to 30°C and Discharging reinitiated at <22.2°C (¶ 6.2.1.2)
Charging	-10.0° C to 22.2° C (14° F to 72° F)	0.0 to 30.0 A	≤ 34.3 V or V/T curves attached	< 1200 psi	22.2°C terminates charging while temp may rise to 25°C and Charging reinitiated at <20°C; 1100 psi terminates charging with 1200 psi upper limit (¶ 6.1.1. step 2 & 3)
Trickle Charging	" "	0.4 to 1.4 A	" " and > 22V	< 1200 psi	22.2°C terminates charge & REE reinitiates at <20°C or pulse chrg (¶ 6.1.1)
Pulse Charging	-10.0° C to 25.0° C	8 ± 2A, 2 ±0.1 min; 0.6±.2A, 13±0.1 min	≥ 31.84V	100 ≤ P < 1200 psi	(¶ 6.1.2)
Conditioning	-10.0° C to 22.2° C	0.0 to 30.0 A	≤ 34.3 V	0 ≤ P < 1200 psi	3 to 5 times at REE discretion (charge, OCV, para 6.2.1 step 2 discharge), and final charge (¶ 6.4.1)
Reconditioning	-10.0° C to 22.2° C	0.0 to 30.0 A	≥ 22 V or any cell voltage reaches 0.9 V	0 ≤ P < 1200 psi	2 times-(charge, discharge and then final charge) (¶ 6.4.2)
Top-Off Charging	-10.0° C to 22.2° C		29.2V ≤ V <29.5V; ≤ 34.3 V or V/T curves attached	< 1200 psi	22.2°C terminates charging while temp may rise to 25°C and Charging reinitiated at <20°C (¶ 6.1.3)
Open Circuit Voltage		Self Discharge	< 29.2 V	< 1200 psi	Trickle charge or discharged open-circuit storage preferable to an open-circuit charged condition REE direction Discharge & Charge or Top-Off Charge (¶ 6.1.3)
6 Hrs< t < 3 Days (any SOC)	-10.0° C to 30.0° C (14° F to 86° F)[2]	Self Discharge	≤ 34.3 V	< 1200 psi	Charge for a period of time of 0.032 times open-circuit hours (¶ 6.3.1)
between 3 and 14 days (any SOC)	-10.0° C to 25.0° C	Self Discharge	≤ 34.3 V	< 1200 psi	Topping charge or discharged open-circuit storage (¶ 6.3.1)
between 14 & 28 days (requires letdown)	-10.0° C to 22.2° C			≥ 0 psi	(¶ 3.2.2)
> 28 days (requires letdown)	-5.0° C to 5.0° C (23° F to 41° F)		Individual Cells <0.3V	≥ 0 psi	(¶ 3.2.2)

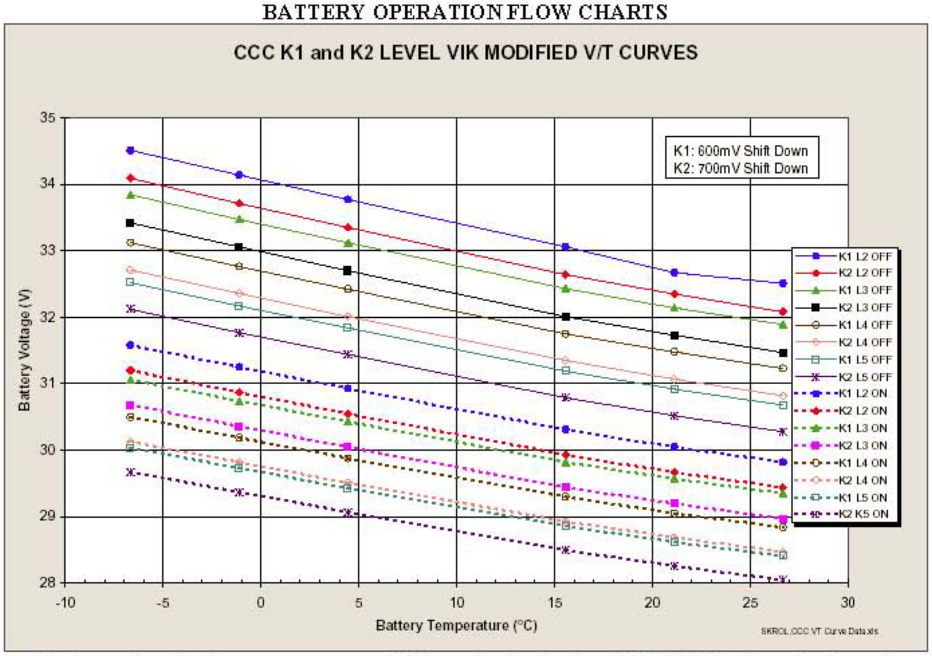
Figure A-1 Battery Limits Compliance Matrix

Page 19 of 29

APPENDIX A
BATTERY OPERATIONAL LIMITS SUMMARY

LMMS/P564384
Baseline
October 24, 2002

APPENDIX B
BATTERY OPERATION FLOW CHARTS



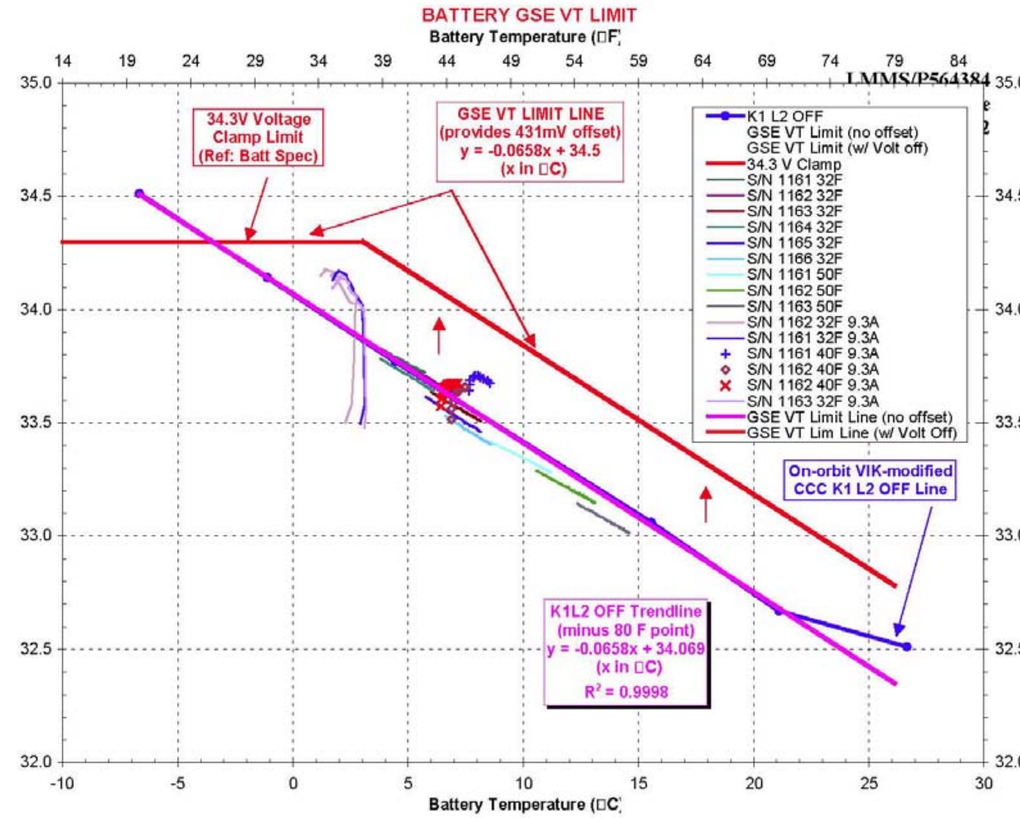
1: During testing, the battery temperature shall be maintained at least 2.8° C (5° F) above the dew point of the battery environment to prevent condensation.

2: Battery temperatures may exceed 30° C (86° F) for no more than 72 hours total (accumulated) time, but at no time shall any battery temperature exceed 37.8° C (100° F).

Figure A-2 VIK Modified V/T Curves

Definitions

Letdown	A final step in a full battery discharge that takes the battery voltage to the lowest state that assures minimum state of charge without the risk of any cell reversal. Requires completion of Section 6.2.1, Step 3b; this is important for storage so that all cells remain below 0.5 V after 24 hours open circuit voltage recovery.
Open Circuit (OCV)	The state of a cell, battery or battery module that precludes the passage of measurable current in either direction. This is achieved by completely disconnecting the terminals of the cell, battery or module, respectively. The BIS in the OPEN position puts a battery in the open circuit state. Open circuit is effectively achieved if the terminals are connected to a device of such high impedance that no measurable current is passed.


BATTERY GSE VT LIMIT
Battery Temperature (□F)
LMMS/P564384
34.3V Voltage Clamp Limit (Ref: Batt Spec)
GSE VT LIMIT LINE (provides 431mV offset) y = -0.0658x + 34.5 (x in □C)
K1 L2 OFF
GSE VT Limit (no offset)
GSE VT Limit (w/ Volt off)
34.3 V Clamp
S/N 1161 32F
S/N 1162 32F
S/N 1163 32F
S/N 1164 32F
S/N 1165 32F
S/N 1166 32F
S/N 1161 50F
S/N 1162 50F
S/N 1163 50F
S/N 1162 32F 9.3A
S/N 1161 32F 9.3A
S/N 1161 40F 9.3A
S/N 1162 40F 9.3A
S/N 1162 40F 9.3A
S/N 1163 32F 9.3A
GSE VT Limit Line (no offset)
GSE VT Lim Line (w/ Volt Off)
On-orbit VIK-modified CCC K1 L2 OFF Line
K1L2 OFF Trendline (minus 80 F point) y = -0.0658x + 34.069 (x in □C) R² = 0.9998
Battery Temperature (□C)

Page 22 of 29

APPENDIX B
BATTERY OPERATION FLOW CHARTS

Battery Operations Flow Charts
The individual operations described in the preceding sections of this handling plan are designed to ensure that the batteries perform optimally and pose minimal risk to personnel and equipment. These operations extend from the arrival of the batteries at LM through launch of the spacecraft. The flow charts contained in this Appendix are intended as a guide to tie together the proper sequencing of these operations.

These flow charts cover four areas of battery activities:

- **The first flow chart (Figure B-1) outlines the sequence of operations to be followed upon receipt.**
- **The second flow chart (Figure B-2) outlines the sequence of operations supporting System Tests.**
- **The third flow chart (in two parts, Figures B-3 and B-4) outlines procedures to be followed at the Launch Site: reconditioning (if necessary) after transport, any final testing, and maintenance of the Flight Battery in a ready state for launch.**

Note:
If any battery temperature, current, voltage, or pressure limit from Section 3.3 or 3.4 is exceeded, IMMEDIATELY discontinue battery electrical activity and alert Battery REE before proceeding.

APPENDIX B
BATTERY OPERATION FLOW CHARTS

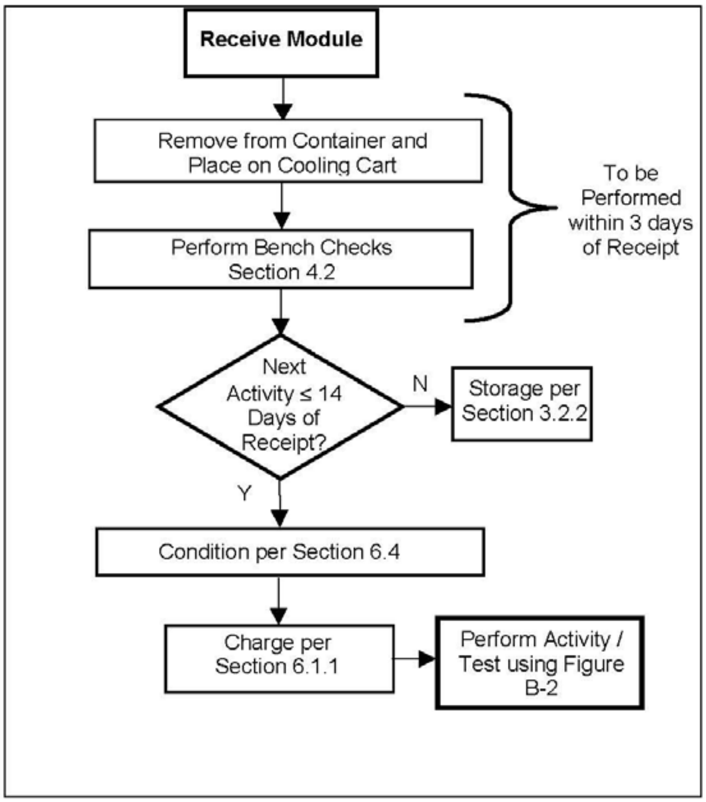


Figure B-1. Flight Battery Integration onto Vehicle.

APPENDIX B
BATTERY OPERATION FLOW CHARTS

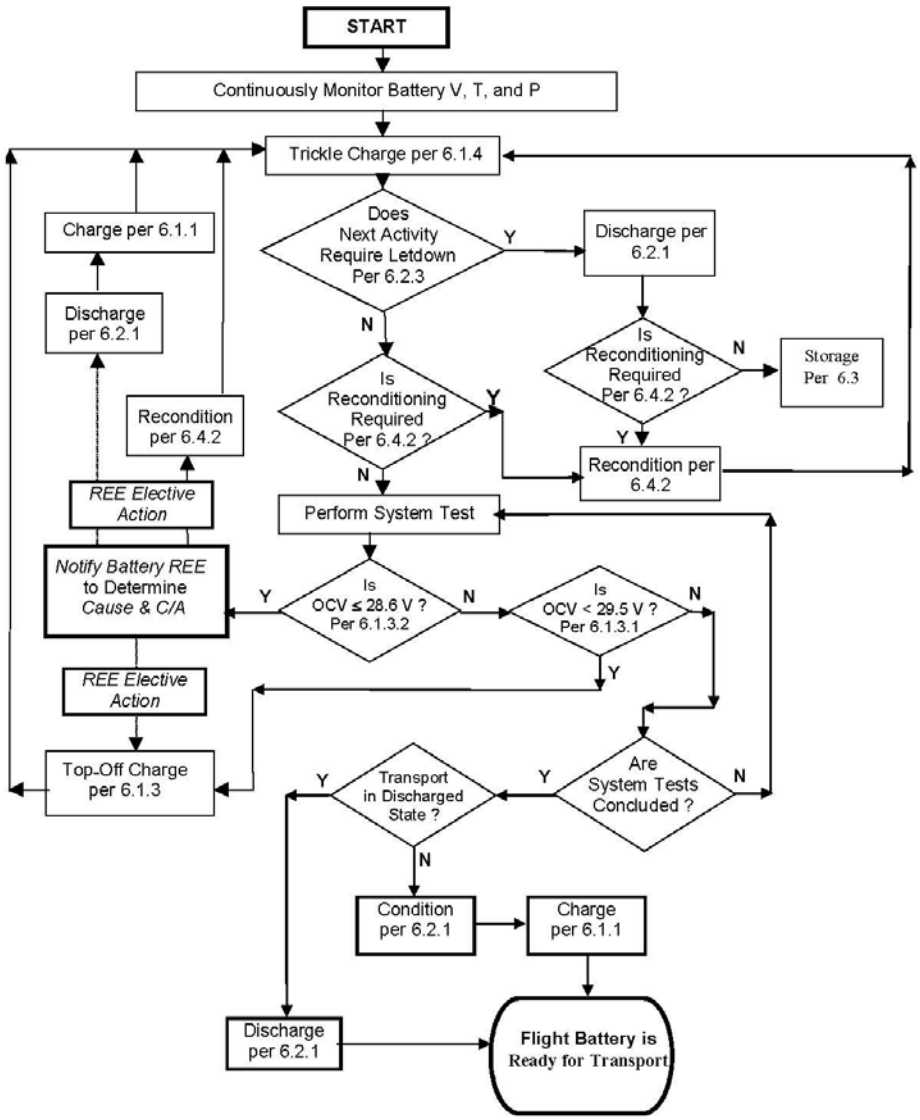


Figure B-2. Flight Battery System Test Activities.

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Baseline
October 24, 2002

APPENDIX B
BATTERY OPERATION FLOW CHARTS

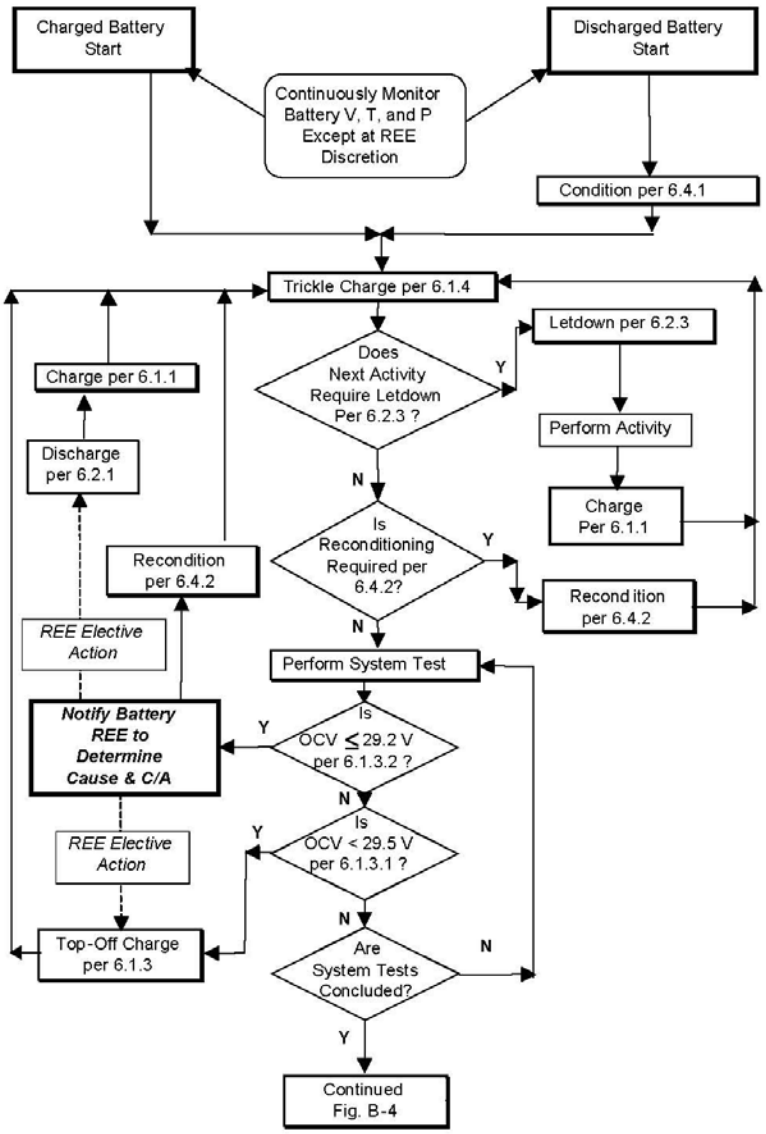

Figure B-3. Part 1 of Flight Battery Launch Site Activities

APPENDIX B
BATTERY OPERATION FLOW CHARTS

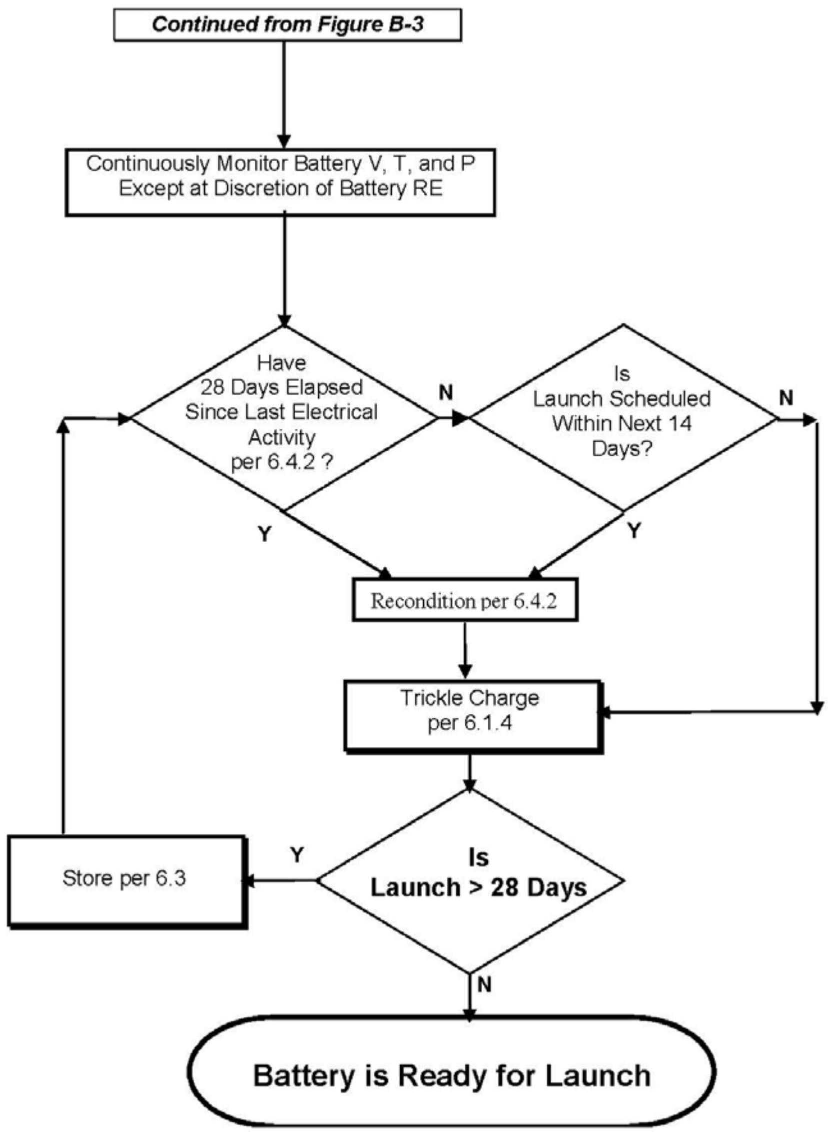

Figure B-4. Part 2 of Flight Battery Launch Site Activities

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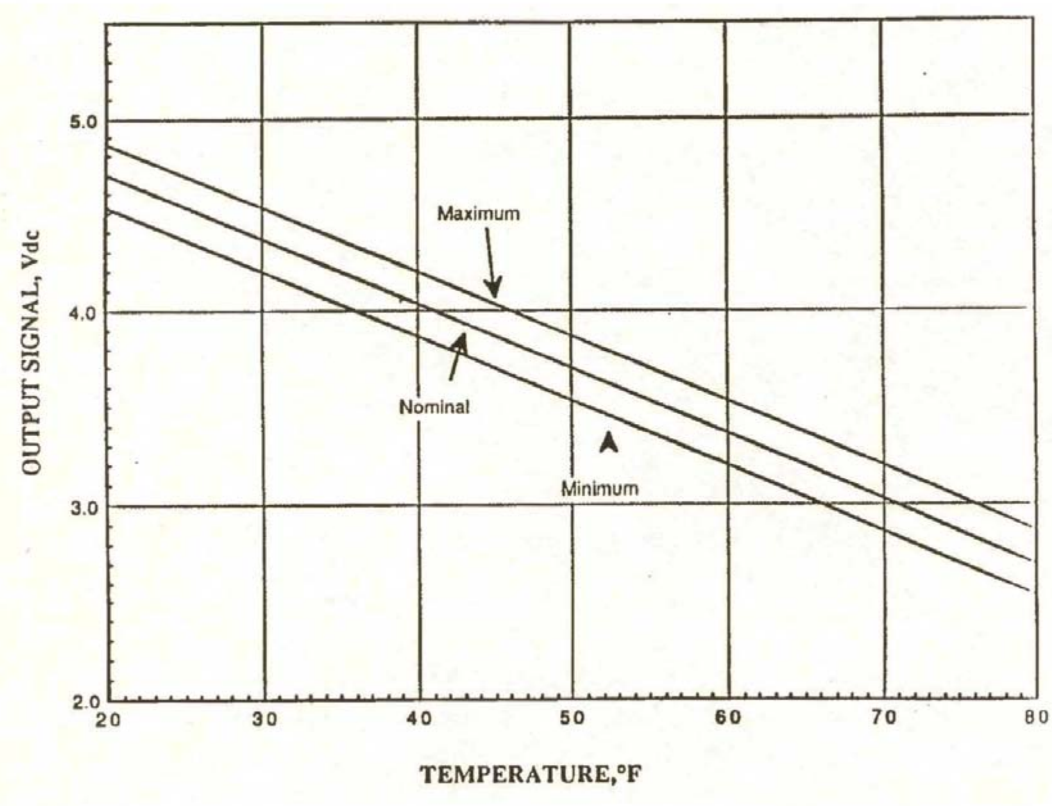
APPENDIX C
BATTERY MODULE HANDLING EQUIPMENT

C-1
Battery Temperature Monitor (RT-1) Graph



LMMS/P564384
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October 24, 2002

APPENDIX C
BATTERY MODULE HANDLING EQUIPMENT

C-2
Charge Control Thermistor Table

TEMPERATURE °F	RT4 & RT5 LOW LIMIT	RESISTANCE NOMINAL	Ohms HIGH LIMIT	RT2 & RT3 LOW LIMIT	RESISTANCE NOMINAL	Ohms HIGH LIMIT
10	17973.41	18529.29	19085.17	8088.03	8338.18	8588.33
11	17487.84	18008.09	18548.33	7880.53	8103.64	8348.75
12	16975.06	17500.08	18025.07	7638.76	7875.03	8111.28
13	16494.87	17005.02	17515.17	7422.69	7652.26	7861.83
14	16027.06	16522.75	17018.43	7212.18	7435.24	7656.29
15	15571.45	16053.04	16534.63	7007.15	7223.87	7440.59
16	15127.83	15595.70	16083.57	6807.53	7018.07	7228.61
17	14698.01	15150.52	15605.04	6613.20	6817.74	7022.27
18	14275.76	14717.30	15158.62	6424.10	6622.70	6821.47
19	13866.96	14295.83	14724.71	6240.13	6433.12	6628.12
20	13469.33	13885.91	14302.49	6061.20	6248.66	6436.12
21	13082.71	13487.33	13891.95	5887.22	6069.30	6251.38
22	12706.90	13099.90	13492.89	5718.10	5894.95	6071.80
23	12341.89	12723.40	13105.10	5553.76	5725.53	5897.29
24	11986.90	12357.63	12726.36	5394.10	5560.93	5727.76
25	11642.32	12002.39	12362.48	5239.04	5401.08	5563.11
26	11307.75	11657.47	12007.20	5086.49	5246.98	5403.24
27	10983.00	11322.68	11662.36	4942.35	5095.21	5248.08
28	10667.87	10997.80	11327.73	4800.54	4949.01	5097.48
29	10362.18	10682.83	11003.11	4662.97	4807.19	4951.40
30	10085.87	10376.98	10688.29	4529.55	4669.64	4809.73
31	9778.21	10080.82	10383.04	4400.19	4536.28	4672.37
32	9499.57	9793.37	10087.17	4274.81	4407.02	4539.23
33	9229.57	9515.02	9800.47	4153.30	4261.76	4410.21
34	8967.99	9245.35	9522.71	4035.60	4160.41	4285.22
35	8714.85	8984.18	9253.70	3921.69	4042.88	4184.17
36	8469.35	8731.29	8993.22	3811.21	3929.08	4046.95
37	8231.88	8486.48	8741.07	3704.36	3818.91	3933.46
38	8002.06	8249.54	8497.03	3600.93	3712.29	3823.86
39	7779.87	8020.28	8280.89	3500.85	3609.13	3717.40
40	7564.53	7798.49	8032.44	3404.04	3509.32	3614.60
41	7356.44	7583.96	7811.48	3310.40	3412.78	3515.17
42	7155.20	7378.49	7597.79	3219.64	3319.42	3419.00
43	6980.80	7175.88	7391.16	3132.27	3229.15	3326.02
44	6772.46	6981.92	7191.38	3047.61	3141.86	3238.12
45	6590.56	6794.41	6996.24	2965.78	3057.49	3149.21
46	6414.75	6613.14	6811.64	2888.84	2975.92	3065.19
47	6244.78	6437.92	6631.08	2810.16	2897.08	2983.98
48	6080.47	6268.53	6466.59	2738.21	2820.84	2905.46
49	5921.63	6104.77	6287.92	2664.73	2747.15	2829.56
50	5768.05	5946.44	6124.64	2595.82	2675.90	2756.18

LMMS/P564384
Baseline
October 24, 2002

APPENDIX C
BATTERY MODULE HANDLING EQUIPMENT

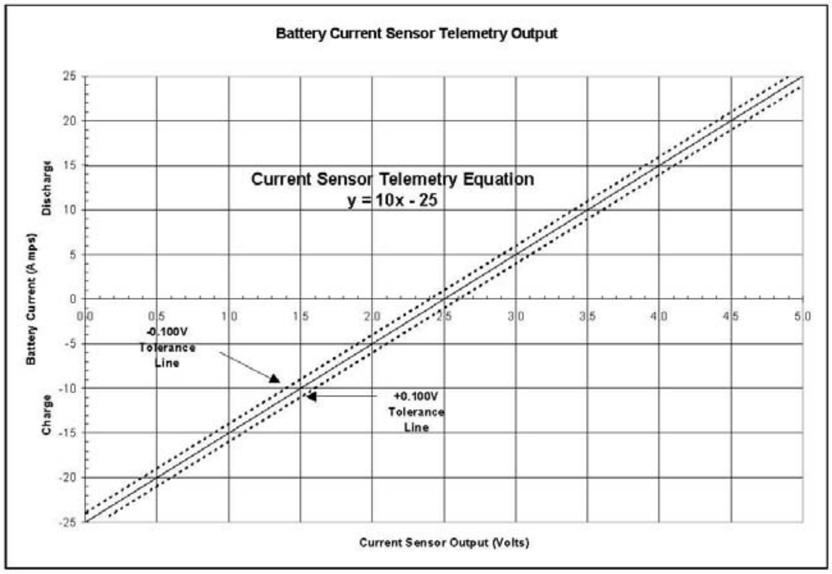
C-2
Charge Control Thermistor Table (Cont.)

TEMPERATURE °F	RT4 & RT5 LOW LIMIT	RESISTANCE NOMINAL	Ohms HIGH LIMIT	RT2 & RT3 LOW LIMIT	RESISTANCE NOMINAL	Ohms HIGH LIMIT.
51	5619.54	5793.34	5967.14	2528.79	2607.00	2685.21
52	5475.90	5645.28	5814.81	2464.15	2540.37	2616.56
53	5336.93	5501.99	5667.05	2401.82	2475.90	2550.17
54	5202.43	5363.33	5524.23	2341.10	2413.50	2485.91
55	5072.22	5229.09	5385.96	2282.50	2353.09	2423.99
56	4948.08	5099.05	5252.02	2225.73	2294.57	2363.41
57	4823.82	4973.01	5122.20	2170.72	2237.86	2304.99
58	4705.24	4850.78	4996.28	2117.36	2182.84	2246.33
59	4590.14	4732.11	4874.07	2065.57	2129.45	2193.33
60	4478.34	4616.84	4755.35	2015.25	2077.68	2139.91
61	4369.82	4504.78	4639.91	1966.33	2027.14	2087.96
62	4263.80	4395.67	4527.54	1918.71	1976.05	2037.39
63	4160.66	4289.34	4416.02	1872.30	1930.20	1988.11
64	4080.02	4165.59	4311.18	1827.01	1883.52	1940.02
65	3981.88	4084.21	4208.74	1782.78	1837.90	1893.03
66	3885.44	3984.99	4104.54	1739.45	1793.25	1847.04
67	3771.10	3887.74	4004.37	1697.00	1749.48	1801.97
68	3678.47	3792.24	3908.00	1655.31	1708.51	1757.70
69	3587.34	3698.29	3809.24	1614.30	1664.23	1714.16
70	3497.52	3605.69	3713.86	1573.88	1622.58	1671.24
71	3408.81	3514.23	3619.66	1533.98	1581.41	1628.85
72	3321.01	3423.72	3528.43	1494.45	1540.67	1586.60
73	3233.92	3333.94	3433.96	1455.27	1500.27	1545.28
74	3147.35	3244.89	3342.04	1418.31	1460.11	1503.92
75	3061.10	3155.78	3250.45	1377.50	1420.10	1462.70
76	2974.98	3066.96	3158.99	1338.74	1380.14	1421.56
77	2888.77	2978.11	3067.48	1299.95	1340.15	1380.36
78	2802.29	2888.98	2975.62	1261.03	1300.03	1339.03
79	2715.33	2799.31	2883.29	1221.90	1259.89	1297.48
80	2627.71	2708.98	2790.25	1182.47	1219.04	1255.61
81	2539.21	2617.75	2698.28	1142.65	1177.99	1213.33
82	2449.65	2525.42	2601.16	1102.34	1136.44	1170.53
83	2358.63	2431.78	2504.74	1061.47	1094.30	1127.13
84	2266.54	2336.84	2406.74	1019.94	1051.49	1083.03
85	2172.80	2239.79	2308.96	977.67	1007.91	1038.14
86	2078.79	2141.02	2205.25	934.58	963.46	992.36
87	1978.93	2040.13	2101.34	890.52	918.06	949.60
88	1878.81	1938.92	1995.03	845.47	871.61	897.78
89	1778.25	1831.18	1888.12	799.31	824.03	848.75
90	1871.03	1722.71	1774.39	751.98	775.22	798.48

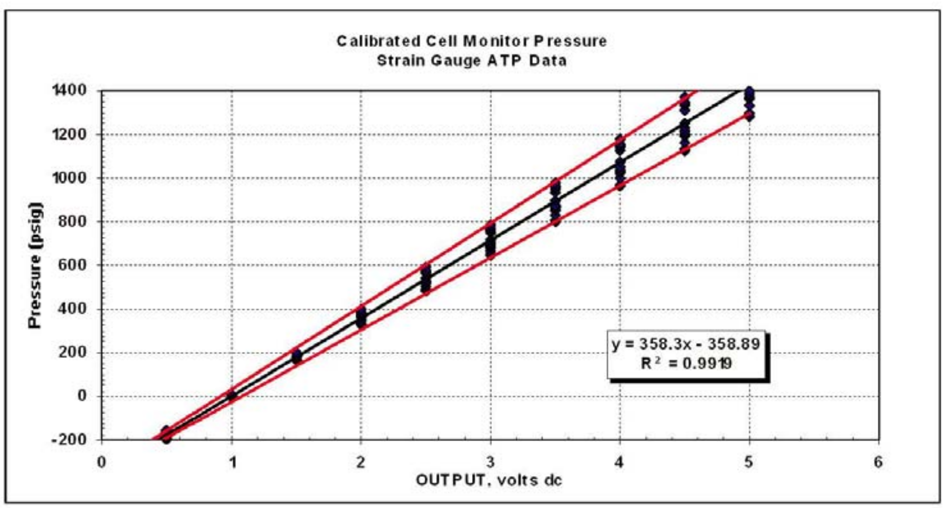
LMMS/P564384
Baseline
October 24, 2002

APPENDIX C
BATTERY MODULE HANDLING EQUIPMENT

C-3
Current Sensor Output Graph



C-4
Pressure Sensor Output Graph



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October 24, 2002

APPENDIX D
BATTERY MODULE HANDLING EQUIPMENT

1. **Battery Module Shipping Container: Part number 4177315-501**
   Purpose: The shipping container provides a safe method of transporting the battery modules. It contains humidity, temperature, and shock sensors to monitor the conditions to which the module is subjected during shipping. Desiccant bags shall be placed inside the container or gas purge will be utilized for cold storage.

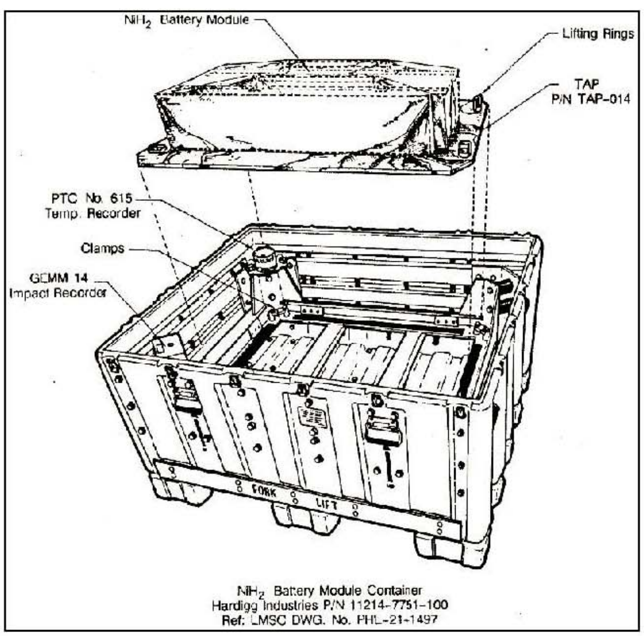

Figure D-1, Shipping Container

APPENDIX D
BATTERY MODULE HANDLING EQUIPMENT

2. Sling/Strongback NiH_2: Part Number 4178052

Purpose: To lift the module from the shipping container. It connects to the Transportation Adapter Plate (TAP) to which the battery module is mounted.

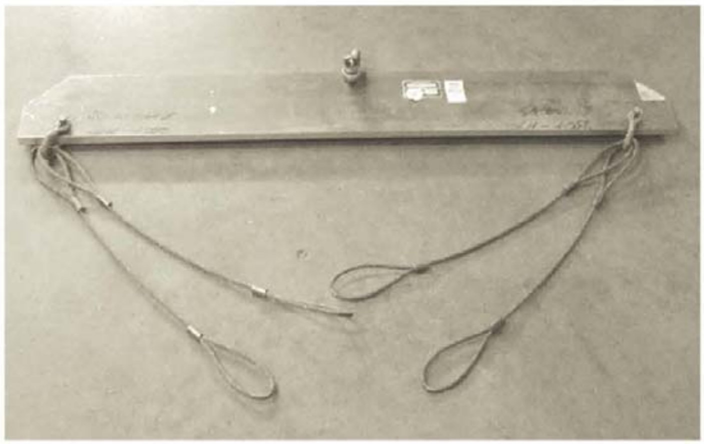

Figure D-2, Sling/Strongback

3. Battery Module Lifting Bracket: Part Number 4177878-503

Purpose: To lift and rotate Battery Module as required. Nameplate weight rating is listed at 550 lbs.

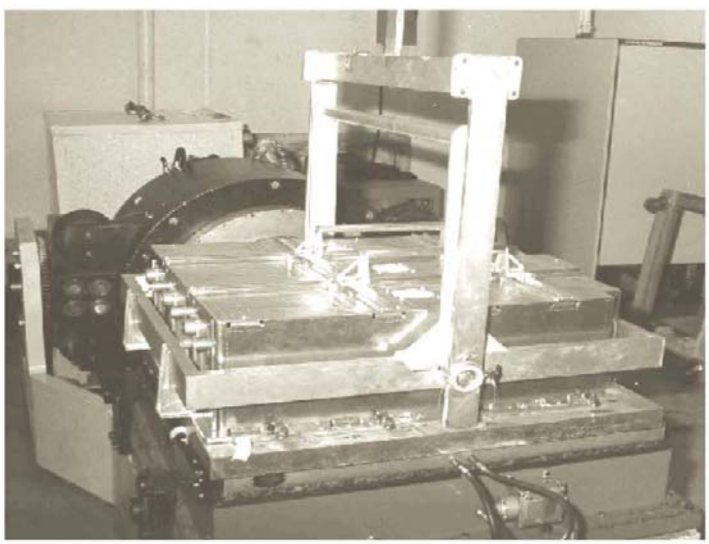

Figure D-3, Battery Module Lifting Bracket

LMMS/P564384
Baseline
October 24, 2002

APPENDIX D
BATTERY MODULE HANDLING EQUIPMENT

4. Nickel Hydrogen Handling Dolly Part Number 4177880-501

Purpose: To supply a surface and means to transport the Battery Module. The surface of the dolly is also a cooling plate which when mated to a cooling system can be used to maintain battery temperature during conditioning.

Figure D-4, Cooling Plate (top)

APPENDIX D
BATTERY MODULE HANDLING EQUIPMENT

5. Walk in Cooler
Purpose: Used to store Battery Modules for long discharged and open circuited periods. The refrigeration system must be monitored, alarmed and able to maintain between –5 °C to +5 °C. The cooler will be located in Bldg 29 Room 160 at GSFC.

6. Break out cables, extension harnesses, Break out boxes and other supporting EGSE used at GSFC and KSC
Will have approved and released drawings as well as certification testing prior to connecting to batteries. Released GSFC procedures will define all required EGSE.

7. Eagle-Picher Portable Battery Test Set, Part Number VMD 725-1

Purpose: Able to perform and acquire all data for all module level tests. Tests shall include battery conditioning, discharge impedance, peak load, and surge load tests. The Test Set will be able to simultaneously monitor all required telemetry for a single module (3 batteries). During testing, the Battery Test Set will acquire pressure, temperature, current, thermistor data, and individual cell voltages. Three battery specific Break Out Boxes will be connected in line with each battery connector to control the test and provide feedback telemetry. A fourth Break Out Box will be used to monitor battery baseplate temperatures via thermocouples to control the cooling system.

Each battery will have a dedicated and properly fused 1000-watt battery charging power supply and a 1500-watt electronic load for discharge.

A computer, monitor, and printer will provide a user interface and record all data. Event summaries such as ampere-hours, watt-hours, volt vs. time, and temp vs. time will be available. Hardware and software automatic test termination will be used to safeguard the Battery Module during charging and/or conditioning.

8. Jackson and Tull Battery Test Set
Purpose: Able to simultaneously either condition or trickle charge each of six batteries (in two modules) while fully monitoring all battery telemetry.

During testing, the Battery Test Set will acquire primary and redundant pressure, temperature and current data, as well as thermistor data, and total cell voltages.

Each battery will have a dedicated properly fused 600-watt power supply for battery charging.

The Battery Interface Box will provide the means to connect all batteries, power supplies, and the data acquisition system. A computer, monitor and printer will provide a user interface and record all data. Event summaries will be made available as requested. Hardware and software automatic test termination will be used to safeguard the Battery Module during charging.

Hardware and software automatic test termination will be used to safeguard the battery module during stand-alone charging activity.

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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 II Appendix A to Part 2 - Volume I.

15. SUBJECT TERMS
Aerospace; Battery; Hubble Space Telescope; Lithium-ion; Nickel Hydrogen

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