NASA/TM-2010-216840
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Wilkinson Microwave Anisotropy Probe (WMAP) Battery Operations Problem Resolution Team (PRT)

Keys, Denney J./NESC
Goddard Space Flight Center, Greenbelt, Maryland

August 2010

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National Aeronautics and
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August 5, 2010

Report Approval and Revision History

Approval and Document Revision History

NOTE: This document was approved at the August 5, 2010, NRB. This document was submitted to the NESC Director on August 9, 2010, for configuration control.

Approved Version:	*Original Signature on File*	8/11/10
1.0	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Mr. Denney Keys, NASA Technical Fellow for Electrical Power	8/5/2010

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Volume I: Technical Assessment Report

1.0 Notification and Authorization

Dr. John H. Day, Chief – Electrical Systems Center at NASA Goddard Space Flight Center (GSFC), requested an independent assessment of the Wilkinson Microwave Anisotropy Probe (WMAP) Battery Operations.

A NASA Engineering and Safety Center (NESC) out-of-board activity was approved December 17, 2009. Mr. Denney J. Keys, NASA Technical Fellow for Electrical Power, was assigned to form a Problem Resolution Team (PRT). The PRT helped assess the flight battery that is currently operating aboard NASA's WMAP. An assessment plan was presented and approved by the NESC Review Board (NRB) on February 4, 2010. A preliminary stakeholder summary was presented and approved by the NRB for approval on May 27, 2010.

The key stakeholders for this assessment are Dr. John H. Day and Peter M. Bay (Mike), Lead Systems Engineer for WMAP Battery Operations, GSFC.

2.0 Signature Page

Submitted by:

Team Signature Page on File - 8/13/10

Mr. Denney J. Keys Date

Significant Contributors:

Mr. Jeff Dermott	Date	Dr. Albert Zimmerman	Date
Mr. Joseph Stockel	Date	Ms. Amri Hernandez-Pellerano	Date
Dr. Hari Vaidyanathan	Date	Dr. Ralph White	Date
Dr. George Dakermanji	Date	Mr. Keith Chin	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	Position/Technical Discipline Team (TDT) Affiliation	Center/ Contractor
Core		
Denney Keys	Lead, NASA Technical Fellow, Electrical Power	GSFC
Dr. John Day	Stakeholder	GSFC
Michael (Mike) Bay	Engineer, Project OC	Bay Engineering Innovations
Joseph Stockel	Senior Consultant	NRO (ret.)
Dr. Albert Zimmerman	Senior Consultant	The Aerospace Corporation
Roger Hollandsworth	Sr. Staff Chemical Engineer	Lockheed Martin (ret.)
Dr. Judith Jeevarajan	Battery Safety	JSC
Dr. Hari Vaidyanathan	Sr. Manager, Technical Services Battery Laboratory/Electrical Power TDT	Lockheed-Martin/COMSAT
Dr. Ralph White	Battery Engineer/Electrical Power TDT	University of South Carolina
Dr. George Dakermanji	Chief Staff Engineer/Electrical Power TDT	MEI Technologies, Inc.
Keith Chin	Power Subsystem Engineer	JPL
Amri Hernandez-Pellerano	Electrical Engineer/Electrical Power TDT	GSFC
Jeff Dermott	Senior Staff Engineer	EaglePicher Technologies
Support		
Donna Gilchrist	Planning and Control Analyst	ATK, LaRC
Loutricia Johnson	MTSO Program Analyst	LaRC
Melinda Meredith	Project Coordinator	ATK, LaRC
Erin Moran	Technical Writer	ATK, LaRC

4.0 Executive Summary

Mr. Denney Keys, the NASA Technical Discipline Fellow for Electrical Power, was requested to form a Problem Resolution Team (PRT) to help assess the health of the flight battery that is currently operating aboard NASA's Wilkinson Microwave Anisotropy Probe (WMAP) and provide recommendations for battery operations to mitigate the risk of impacting science operations for the rest of the mission.

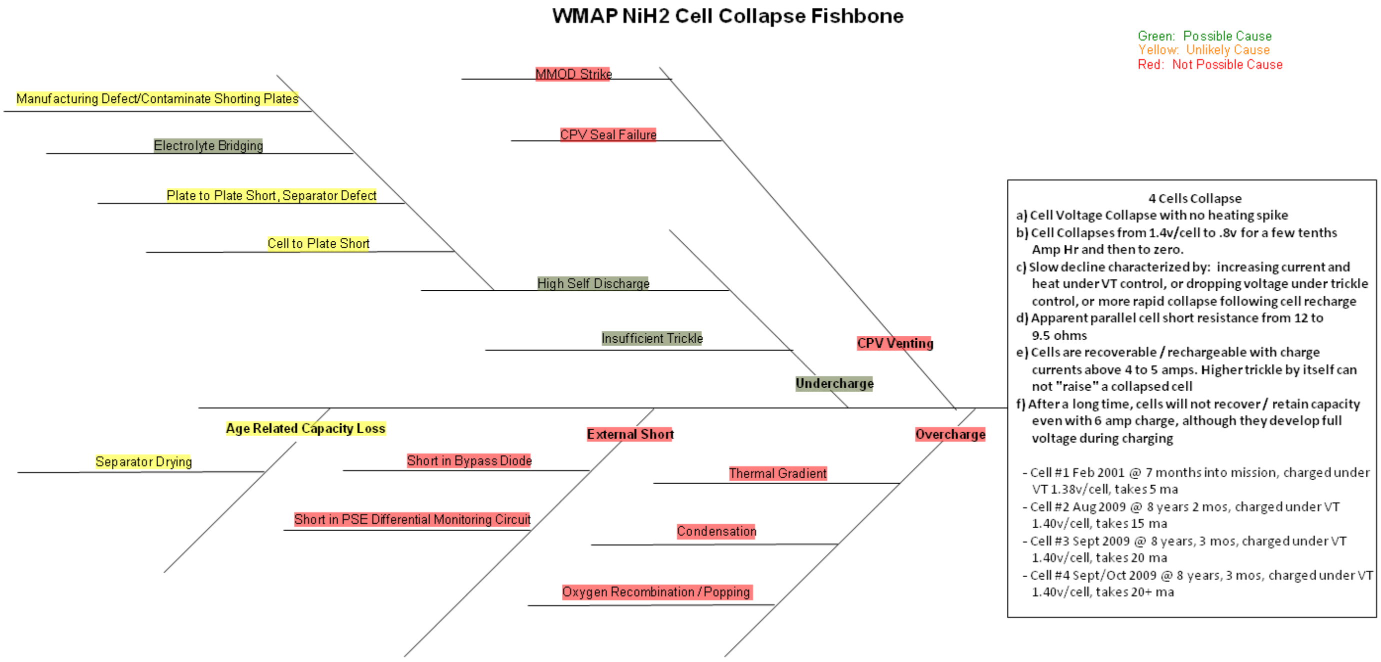
WMAP was launched June 30, 2001 to map the Cosmic Microwave Background radiation and produce a fine-resolution full-sky microwave map of the universe. WMAP was originally designed for duration of 2 years of mapping operations but, has been on mission extensions and is currently scheduled for science operations through August of 2010.

The WMAP Common Pressure Vessel (CPV) Nickel-Hydrogen (NiH_2) battery suffered a series of cell voltage drops. The first cell voltage drop occurred in February of 2002 and four more cells experienced significant voltage drops between August and December 2009. This recent clustering of cell voltage drops over 5 months is of concern because WMAP can tolerate only two more cells with such voltage drops before potentially having to either shed loads or alter science operations. Also, there are other NASA spacecraft that use CPV-type NiH_2 battery technology (e.g., Solar Terrestrial Relations Observatory (STEREO) Solar Radiation and Climate Experiment (SORCE) and Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER)) for which understanding the failure mechanism and mitigating operational strategies may be valuable.

The two major objectives were to: 1) assist the WMAP Flight Operations Team with short-term tactics to restore and maintain a higher battery voltage, and 2) devise a longer term operations strategy intended to prevent or arrest further decline.

During this assessment the WMAP Battery Operations PRT attempted to identify potential causes for the observed behavior as well as to devise a defined test plan utilizing spare WMAP cells and aged Hubble Space Telescope (HST) battery cells to determine: (1) whether battery degradation effects are age related, (2) whether battery degradation is related to on-orbit battery operating parameters, or (3) whether observed behavior may be linked to both age and operating environment.

Potential causes for the observed cell collapses considered during this assessment are believed to be limited in nature based on team member experience. The basic causes identified and considered have been captured in the fishbone chart Figure 4.0-1. Generally speaking, most external causes identified are able to be readily dismissed because they would have affected the battery at a CPV level (2 series cell voltage impacts) as opposed to the observed behavior limited to one of the two internal cells in the CPVs for each event.



4 Cells Collapse

a) Cell Voltage Collapse with no heating spike
b) Cell Collapses from 1.4v/cell to .8v for a few tenths Amp Hr and then to zero.
c) Slow decline characterized by: increasing current and heat under VT control, or dropping voltage under trickle control, or more rapid collapse following cell recharge
d) Apparent parallel cell short resistance from 12 to 9.5 ohms
e) Cells are recoverable / rechargeable with charge currents above 4 to 5 amps. Higher trickle by itself can not "raise" a collapsed cell
f) After a long time, cells will not recover / retain capacity even with 6 amp charge, although they develop full voltage during charging

- Cell #1 Feb 2001 @ 7 months into mission, charged under VT 1.38v/cell, takes 5 ma
- Cell #2 Aug 2009 @ 8 years 2 mos, charged under VT 1.40v/cell, takes 15 ma
- Cell #3 Sept 2009 @ 8 years, 3 mos, charged under VT 1.40v/cell, takes 20 ma
- Cell #4 Sept/Oct 2009 @ 8 years, 3 mos, charged under VT 1.40v/cell, takes 20+ ma

Figure 4.0-1. WMAP NiH_2 Voltage Collapse Fishbone

In order to identify possible contributors to cell collapse events, the PRT determined the need to evaluate comparable battery operational characteristics via testing. After reviewing all available candidate cells best suited for supporting testing for this assessment, selection of the WMAP flight spare battery and various HST battery cells were considered to best represent the configuration and age characteristics needed to perform the evaluation. Once the cells and battery were obtained, the PRT proceeded to develop a battery cell test plan based on experience and intended to maximize the chances of successful duplication and determination of observed anomalous behavior. The battery cell test plan was developed acknowledging the need to relatively quickly determine what may be causing the anomalous behavior experienced on-orbit with an expressed desire to potentially identify and test any, and all, possible means to improve the battery condition and state of health. Given the long period of on-orbit operations involved, prior to identifying significant degradation, the testing required accelerating conditions thought to be most likely linked to the problems encountered. In order to accomplish the task, the utilization of the flight spare battery subjected to similar on-orbit operating conditions (specifically temperature and trickle charge rates) was observed to confirm a significant capacity walk-down while operating under low level trickle charge rates over a relatively short period of 2 weeks. With this knowledge in hand, the test battery was then subjected to a controlled discharge to a remaining value roughly comparable to a 10 percent state of charge (SOC) (based on available pressure measurements) and allowed to continue operating under a low trickle charge rate. This induced reduction in capacity was the assumed continuation of the capacity walk-down as seen in the initial two-week period.

During the second portion of the testing at low SOC, the WMAP test battery encountered a sudden voltage drop response, described in detail in Section 7.2, similar to that experienced on-orbit with even a second CPV showing some signs of potentially following suit, if given enough time.

In parallel with the WMAP test battery, sample HST cells were also subjected to similar temperature and trickle charge rate testing in a specific attempt to identify any potential age or design specific related effects from the operating conditions. The age effects were believed to be especially relevant to the HST cells as they are all approximately 19 years in age with various operational lifetimes ranging from stored for the entire lifetime to operating on-orbit for the same period. Additionally, the HST cells are a design having single stacks in individual pressure vessels (IPV cells), and are thus not subject to potential inter-stack electrolyte bridging that is considered possible in the CPV cell design. If age or internal design related factors were the root cause for performance issues under the conditions presented, the HST cells were believed to be the best available NiH_2 cells to produce the desired results and gain any available insight into the WMAP performance issues.

Ultimately, a definitive root cause for the WMAP on-orbit anomalous behavior could not be determined based solely on the tests conducted with the WMAP spare battery CPVs or the HST IPV cells. The team consensus theory for the anomalous behavior exhibited on-orbit was determined to be related to electrolyte bridging between the cells within a CPV resulting in either electrolyte depletion within one of the two cell stacks (and ultimately electrolyte starvation or drying out of one cell stack) or an ionic transport mechanism that caused similar charge retention depletion of one of the two cell stacks.

In the more pertinent case of the WMAP spare battery testing the cell collapse was effectively recovered using a single small discharge followed by a relatively low (C/10) charge cycle and has since demonstrated nominal behavior in testing. This approach was also invoked with the on-orbit battery and appears to have provided only temporary improvement in voltage characteristics with nearly all previously collapsed cells ultimately recollapsing despite increased trickle charge levels. Specifically in the case of on-orbit performance, the WMAP battery initially displayed somewhat similar improvement signs and behavior to this operation but soon afterward displayed cell voltage collapses. Despite utilizing similar pulse charges and trickle charge rates as those used unsuccessfully on-orbit, in the case of the test battery the discharge/charge cycle and subsequent pulse charging has clearly resulted in the collapsed cell returning to in-family performance similar to all of the other cells in the battery.

It would be desirable to continue testing the WMAP spare battery to assist in determining the root cause of the flight battery's anomalous on-orbit behavior but, given the observed behavior to date, any long term test results would not likely be obtained in time to benefit the WMAP mission during its remaining lifetime.

The relevant findings and NESC recommendations derived from this assessment are as follows:

F-1. The observed WMAP flight battery on-orbit behavior with the WMAP flight battery was atypical for IPV NiH_2 cells and appears to be unique in nature for CPV cells.

F-2. Battery voltage reductions of 1.4V are consistent with the collapse of an individual cell due to complete self-discharge.

F-3. The collapsed cells do not accept charge efficiently after their collapse. Most of the recharge energy is dissipated as heat and little was converted into stored energy.

F-4. The trickle charge resulting from the chosen V/T level of 1.4V per cell was insufficient to maintain a consistent SOC beyond 8 years of life. Based on standard NiH_2 battery test experience and typical recommendations from the battery vendor (EaglePicher Technologies), the WMAP CPV based battery capacity was insufficiently maintained on-orbit using a temperature compensated voltage (V/T) charge maintenance at the level implemented.

F-5. The prelaunch decision to eliminate on-orbit pressure measurements using the available strain gage cells severely limited the ability to determine if the battery was being properly maintained.

F-6. The WMAP battery thermal design severely limits the ability to properly rebalance or recharge cells after discharge has occurred and the cells do not accept recharge (radiator designed for nominal rejection of only 5 watts which limits prolonged charging above trickle charge rate due to potential thermal runaway).

F-7. Test results indicate that IPV cells as designed are not as susceptible to capacity losses attributed to electrolyte bridging.

F-8. With two series connected cell stacks within a single pressure vessel, charge transport mechanisms can exist between the cells potentially degrading performance in one, or both, cell stacks.

The NESC recommendations, directed to the WMAP project, are based on the likelihood that an electrolyte bridge exists between the two cells of a CPV:

R-1. Maintain a minimum trickle on the WMAP NiH_2 battery at a rate of at least C/200, independent of the voltage clamp setting.

R-2. Periodically charge the WMAP NiH_2 battery to assure the remaining active cells do not operate close to a fully discharged state.

- Including current pulsing if necessary.
- Battery temperature should be maintained below +10°C at all times.

R-3. Increase the trickle charge rate incrementally, if needed, to maintain voltage stability and performance up to the maximum recommended battery temperature of +10°C.

R-4. Perform discharge/charge cycling, or a period of open-circuit followed by charge, at least once to redistribute electrolyte and to characterize the response.

- Precautions should be taken to assure no other CPV cells collapse in voltage during the discharge by discontinuing discharge as soon as battery indicates a sharp drop in voltage consistent with one or more cells.
- The net ampere-hour charge should always exceed the ampere-hour net discharge in order to assure battery cells are not inadvertently undercharged prior to the next contact. At a minimum at least a 1.1 recharge ratio should be used, preferably more.
- Close monitoring of voltage and temperature, particularly during the discharge, should be performed.

5.0 Assessment Plan

The PRT investigated the anomalous behavior of the WMAP battery and evaluated alternative operational considerations to safely improve the operational lifetime of the WMAP spacecraft. The evaluation consisted of reviewing historical performance data and available battery parameters; identifying and executing additional data, tests, and modeling required to develop an understanding of the present state of the WMAP battery; performing comparable stress tests and, if appropriate, destructive physical analysis (DPA) on any available WMAP flight lot cells; and implementing any identified on-orbit performance tests. The PRT performed the following tasks during the evaluation:

- Reviewed historical data related to WMAP mission, including battery parameters, battery performance, as well as monitoring operating status of the on-orbit battery performance throughout the assessment.
- Identified any additional data, information, tests, or modeling needed to more effectively evaluate current battery status.
- Performed a comparable electrical stress test that duplicated on-orbit conditions as reasonably possible (charge conditions and temperature) on a WMAP spare flight battery cell to evaluate possible internal chemistry effects. DPA in the original plan had not been implemented because no specific issue with test cells has been identified to date and a DPA was not believed applicable to increasing knowledge base for assessment.
- Implemented additional identified on-orbit tests as a result of assessment investigation/modeling/and testing performed, coordinated through WMAP Flight Operations. Throughout the assessment various operating parameter changes (such as charge rates, frequency of charge events, and thermal limitations) were provided by the PRT to the WMAP project for consideration and implementation.
- Identified all potential candidates associated with the battery performance degradation.
- Developed a comprehensive list of all practical means or recommendations to reverse or stem battery degradation.

Historical background as provided by the WMAP POC is provided in Appendix A.

6.0 Background and Problem Description

WMAP was launched in June 2001 to map the cosmic microwave background radiation and produce a fine-resolution full-sky microwave map of the universe. WMAP was originally designed for a 2-year mission but has approved funding for science operations through August 2010.

The WMAP 23 ampere-hour CPV NiH_2 battery, which contains two series-connected cells in each of 11 pressure vessels, has suffered a series of cell voltage drops. The first cell voltage drop occurred in February of 2001, and four more cells experienced significant voltage drops between

August and December 2009. The clustering of cell voltage drops over 5 months is of obvious concern because WMAP can tolerate only two more cells with such voltage drops (1.4 V) before having to shed loads and altering science operations. After the 5th cell collapsed, the concern had reached a point where some action was deemed necessary by both the project and supporting engineering directorates and subsequently a series of charge cycles were performed that recovered some of the collapsed cells, at least temporarily, with four cells experiencing re-collapse again over the past few months and with anomalous performance activity still occurring to date.

There are other NASA spacecraft (MESSENGER launched in August 2004 and the two STEREO spacecrafts[1] launched October 2006) for which understanding the failure mechanism and mitigating operational strategies *could be* valuable. These spacecraft use identical 23 ampere-hour CPV-type NiH_2 battery technology and have similar operational parameters (mostly full sun orbits). These spacecraft, which have consistently been *maintained differently since launch with higher trickle charge levels,* have not experienced any evident issues related to capacity or voltage loss to date. MESSENGER is scheduled for Mercury orbital insertion in March 2011 and will perform surface mapping once there. The STEREO spacecraft were originally designed to meet a 2-year mission, which, like WMAP, has been surpassed and funding extended with mission operations now approaching 4 years.

6.1 Spacecraft Overview

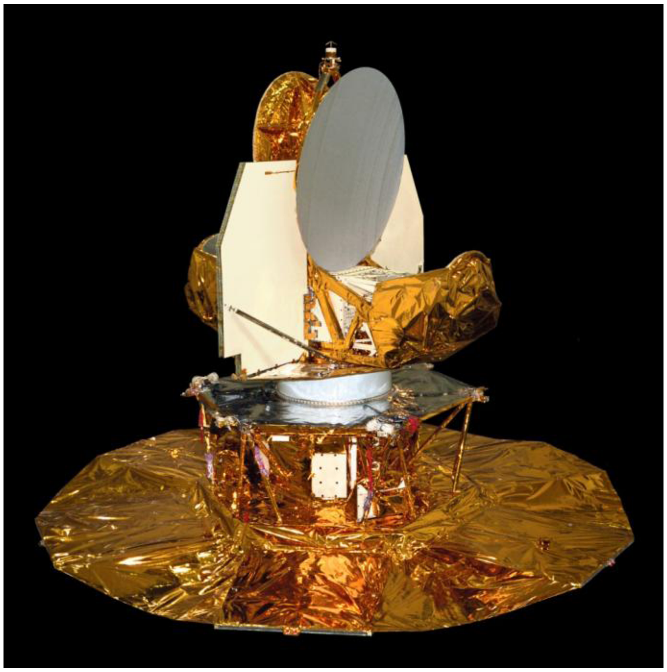


Figure 6.1-1. Spacecraft Overview - WMAP Observatory with Sunshade shown (bottom)

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[1] *MESSENGER was launched in August 2004 and the two STEREO spacecrafts were launched in October 2006.*

Background on the WMAP mission and power system as provided by excerpts from a paper written by Castell, et. al., titled ***Closed Loop Software Control of the MIDEX Power System***[2],

> *"The Microwave Anisotropy Probe (MAP) is a NASA science satellite designed to measure temperature gradients in the cosmic background radiation……The power requirements for this satellite are 325 Watt-hours from a combination of battery and solar array power during launch, 420W for a maximum of 120 minutes during maneuvers, and 400W continuously while in orbit. The major power loads are three reaction wheels (each having 125W peak power, 17W average), which will turn on during the launch sequence and a 150W microwave radiometer which will be operated while the satellite is in orbit. Some of the other critical loads are the spacecraft's computational hub, the command and data handling unit (C&DH), the transponder which is the communications link to the ground, and the Attitude Control Electronics (ACE) which performs the spacecraft navigation and attitude control. Power is supplied by 22 NiH_2 battery cells for the launch phase and maneuvers. The solar array is composed of 12 segments of gallium arsenide (GaAs) solar cells."*

With regard to the WMAP electrical bus architecture, the battery and solar arrays are connected directly to the main bus in the power system electronics and the WMAP type architecture is frequently used in robotic spacecraft to minimize mass and parasitic losses. This bus architecture is referred to as a direct energy transfer (DET) system and results in the battery voltage defining the electrical power system operating voltage since it is connected directly across the bus to ground. In fully regulated power systems, there is usually a bi-directional converter between the power bus and the battery, which would allow a boost (or buck) conversion capability as well as the ability to operate a battery at a significantly lower voltage without concerns for power converter drop-outs. In the case of WMAP, any change in battery voltage is directly translated to an equivalent change in bus voltage. As with most 28V nominal bus systems, load-based direct current to direct current (DC/DC) converters are usually designed to operate reliably down to a value of approximately 20V. As such, the design and verification range for bus operations is usually specified between 21-35V. There are multiple aspects of concern to the WMAP mission if the battery voltage drops, which include the need for more heater cycling (which significantly affects science data due to thermal excursions) to maintain critical temperatures and reduction of positive power margin availability from the solar array as the operating point on the array is lowered. If the voltage drops low enough to cause disruption in the instrument operation, it most likely would not be recoverable and the mission would end. For WMAP, the electronics that regulate the solar array power and perform the battery charging are both located in the power system electronics (PSE) unit.

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[2] Closed Loop Software Control of the MIDEX Power System, Karen Castell, Amri Hernandez-Pellerano, Margaret Wismer, 1998 IEEE Aerospace Conference Proceedings

The commanded battery current is calculated in software based on the SOC and the temperature compensated voltage (V/T) of the battery cells. The temperature-compensated voltage levels and ampere- hour integration constants are stored as tables in memory. Figure 6.1-2 shows the overall WMAP power system architecture.

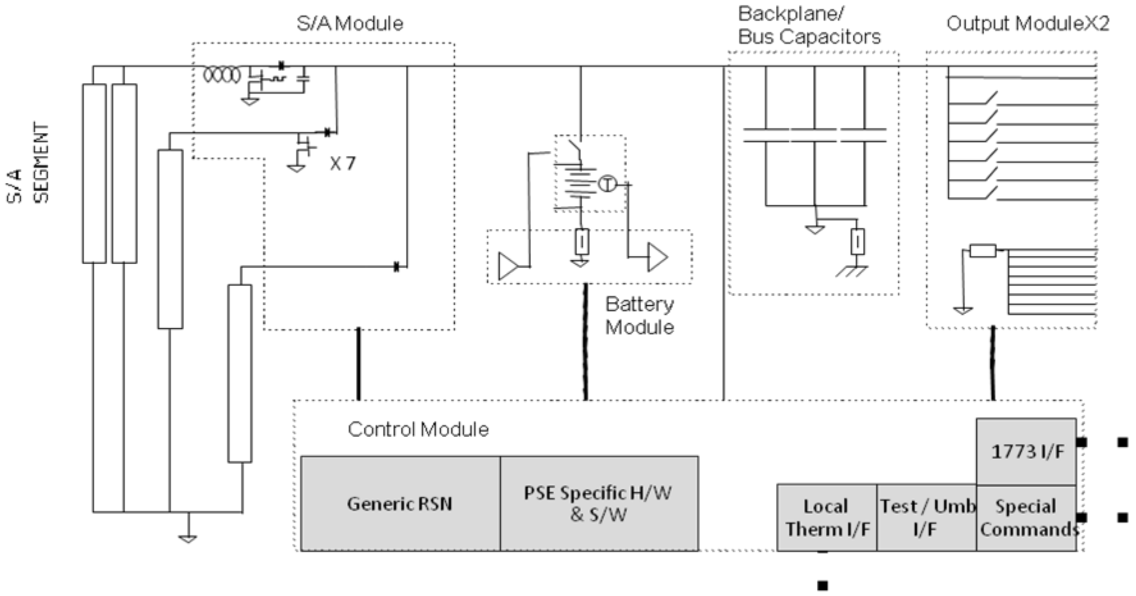

Figure 6.1-2. WMAP Electrical Power System Block Diagram

6.2 WMAP Battery Background and Overview

Figure 6.2-1 shows the WMAP flight battery during processing prior to launch. The WMAP battery comprises 11 CPV NiH_2 battery cells and a total nameplate storage capacity of 23 ampere-hours. The CPVs used for WMAP each contain two individual NiH_2 battery cell stacks within the pressure vessel and are connected internally in series. The terminals on top of the CPV cells provide the positive (+) and negative (–) connections for the CPV. While the battery was originally designed and built to provide an ability to monitor two of the CPV internal pressure measurements via strain gages, pressure measurements are the most reliable means to determine the SOC in NiH_2 cells on-orbit, mounted on the respective cells, the pressure strain gage measurement capability was disabled within the power system electronics prior to launch as a result of electromagnetic interference (EMI) issues noted during integration and test activities. While there is not definitive information readily available to the PRT to describe the detailed circumstances surrounding the discussions and ultimate decision to disable the pressure measurement capability, the information that has been provided indicates the decision was endorsed, or at least deemed acceptable, by the GSFC engineering and Systems and Mission Assurance communities and was apparently also determined a minimal risk to meeting the designed 2-year mission.

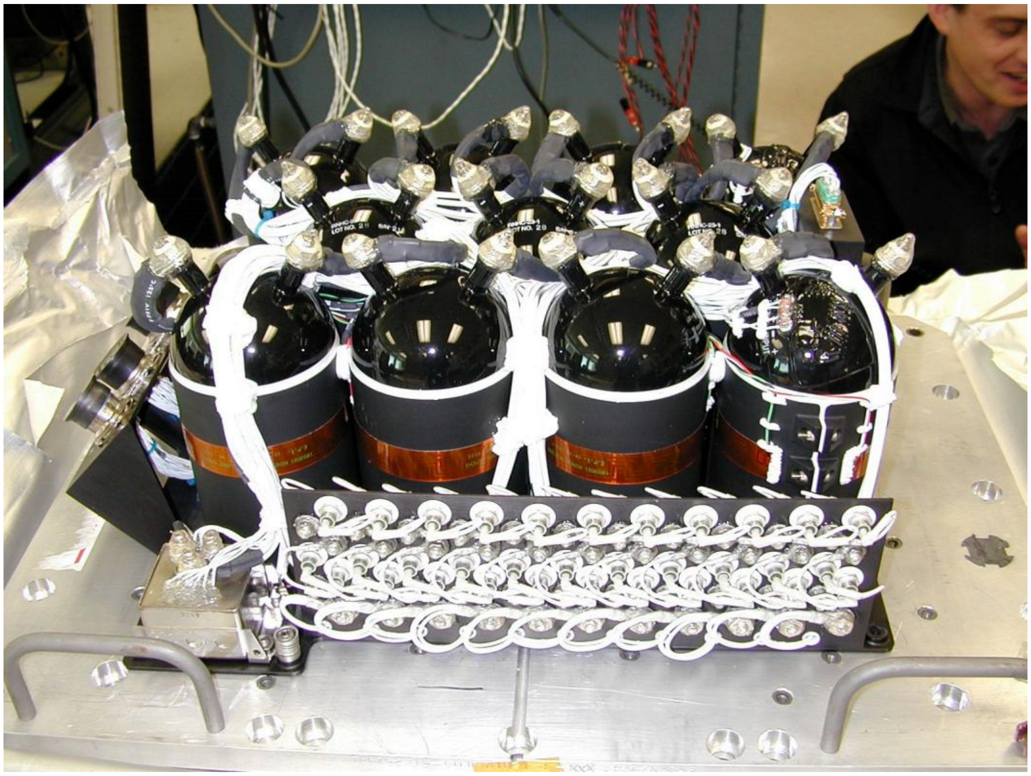

Figure 6.2-1. WMAP Flight Battery During Processing

Without battery pressures to rely on for evaluating the on-orbit status of the battery, the WMAP project and GSFC engineering directorate apparently intended to rely solely on the temperature-compensated V/T clamp feature within the PSE to maintain the battery state of charge. The desired battery voltage is designed to be maintained using automatically adjusted commanded trickle charge current maintenance using a feedback loop within the PSE. The prescribed charge current value is then automatically adjusted according to programmed software table values that depends on the programmed voltage and temperature value of the thermistor measurement within the battery. Use of V/T control management techniques for battery charge maintenance is common, particularly for Low Earth Orbit (LEO) missions where minimizing stress and over shoot of battery voltage during recharging is desired however, once the prescribed energy balance is reached for LEO missions the charge controller normally reverts to a constant current charge mode at a fixed trickle charge rate of at least C/200 (this is a typical description of current charge value based on the nominal battery amp-hr capacity "C" divided by 200). For example, if C = 20 Ah, the capacity, or 20, would be divided by 200 to provide the charge current value of 0.1A. However, V/T charge control has never been used or validated for charge management of nickel hydrogen batteries in applications such as WMAP, involving many years of continuous V/T control with no significant charge/discharge cycling or battery reconditioning.

From a historical perspective, approximately 6 months after launch, the telemetry for battery voltage and temperature displayed evidence of a significant and rapid drop in voltage and coinciding increase in temperature indicating an apparent short circuit problem with one of the 22 battery cells. The on-board fault management detected the event and was pre-programmed to respond to the change by reducing the V/T clamp voltage by three levels (which corresponds to approximately 1.2V). While it is unclear if the initial cell collapse experienced in 2001 was a result of undercharging or an internal failure mechanism, there was no attempt made at that time to recover the cell. According to information gathered during discussions with engineering directorate and WMAP project personnel, the failure in 2001 was believed at the time to be the result of an internal short caused possibly by metallic particles or foreign object debris (FOD) trapped in the cell during fabrication. This theory of the initial on-orbit cell failure was considered likely due to the experience resulting from a similar failure of a battery cell during initial battery testing (failure in that case was confirmed using X-ray and DPA on the affected cell replaced in the flight battery). The conclusion that only a single shorted cell occurred on-orbit was based on the continuation of operations with only the observed loss of one cell in equivalent voltage. If the failure had been a result of an open circuit, the associated bypass switches included in the battery design would have activated and the overall voltage loss experienced would have been the equivalent of two cells (bypass switch is designed to remove an entire CPV). A copy of the DPA performed on the cell in question was provided by the battery vendor and is included in Appendix E.

Figures 6.2-2 and 6.2-3 are intended to show general battery historical performance information as well as a slightly more detailed display of a “typical” cell collapse event experienced by WMAP, respectively. These figures provide evidence of the significant degradation of the battery voltage characteristics and, if left uncorrected would have likely resulted in complete bus voltage operational collapse in a matter of only 2-3 weeks after the 5th cell collapsed, based on the observed frequency rate of collapse.

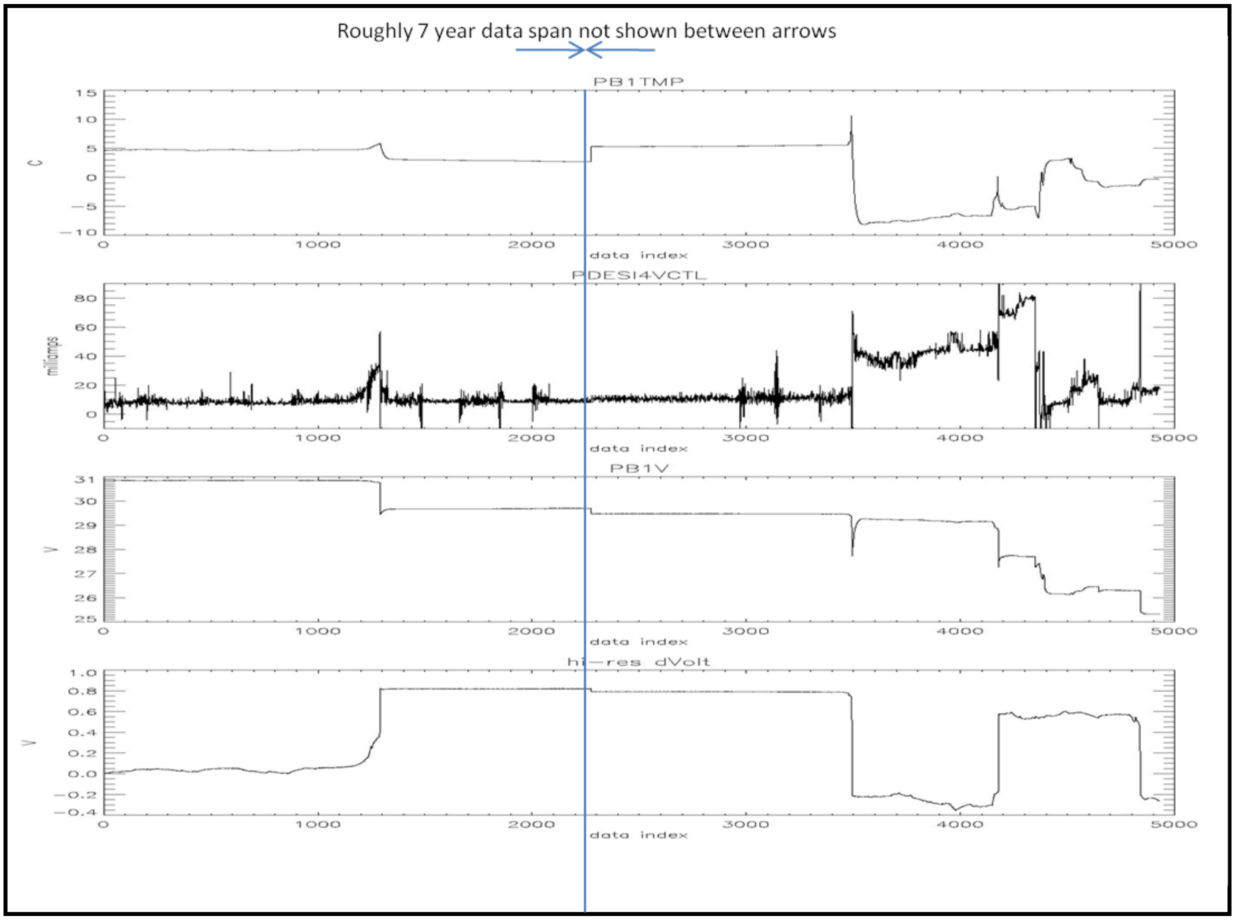

Figure 6.2-2. Historical Perspective of Electrical Power System Operations Up to Anomaly

Figure 6.2-2 shows the battery related telemetry values received from WMAP over the course of the mission up to the events triggering this assessment. From top to bottom, the plots display the primary battery cell temperature measurement, charge or discharge current, battery voltage, and differential voltage (corrected for the uneven distribution of cells). The differential voltage telemetry value represents a corrected voltage measurement comparison of the 2 halves of the battery utilizing a voltage tap incorporated in the middle of the battery. Since the battery is designed with an uneven number of CPVs (11), the actual differential measurement tap is between the 5th and 6th physical CPVs and the comparison circuit in the PSE appropriately designed (offset) to accommodate the difference of one CPV voltage between the two halves. This measurement parameter is typically designed to provide insight into differential changes within the battery such as cell voltage divergence.

As seen in the figures, a typical cell voltage collapse event coincides with battery temperature increase and differential voltage shift. A better view of a representative cell voltage collapse event along with the available telemetry information is provided in Figure 6.2-3.

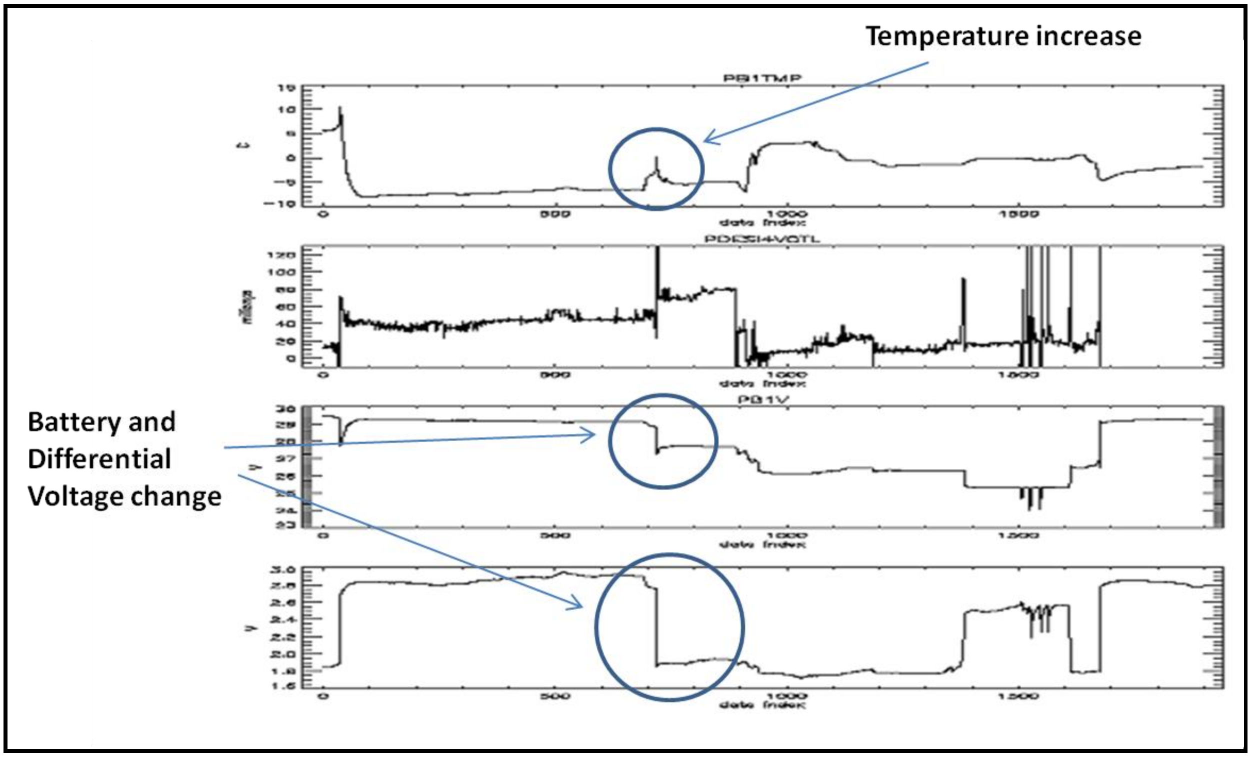

Figure 6.2-3. Close-up View of Typical On-Orbit Cell Collapse Events

Of note, during the events encountered is the characteristic increase in temperature before (and during) the event coupled with the charge current response from the power system attempting to maintain the commanded V/T clamp voltage. According to information provided by the WMAP project team regarding nominal operations, the power system was not designed to attempt to recover any particular cell voltage collapse during the event but, instead was designed to mitigate the possibility of overcharging the battery if an internal cell short were to occur. Therefore, when the on-board software algorithm sensed a sudden shift of more than approximately 0.5V in the differential voltage it responded by lowering the commanded clamp voltage by roughly the equivalent of one cell in voltage (response designed in the failure detection and correction software would lower the V/T level by 3, or approximately 1.2V). A plot of standard V/T curves associated with NiH_2 cells is included in Appendix D for reference.

Figure 6.2-4 provides the basic design characteristics for a typical CPV.

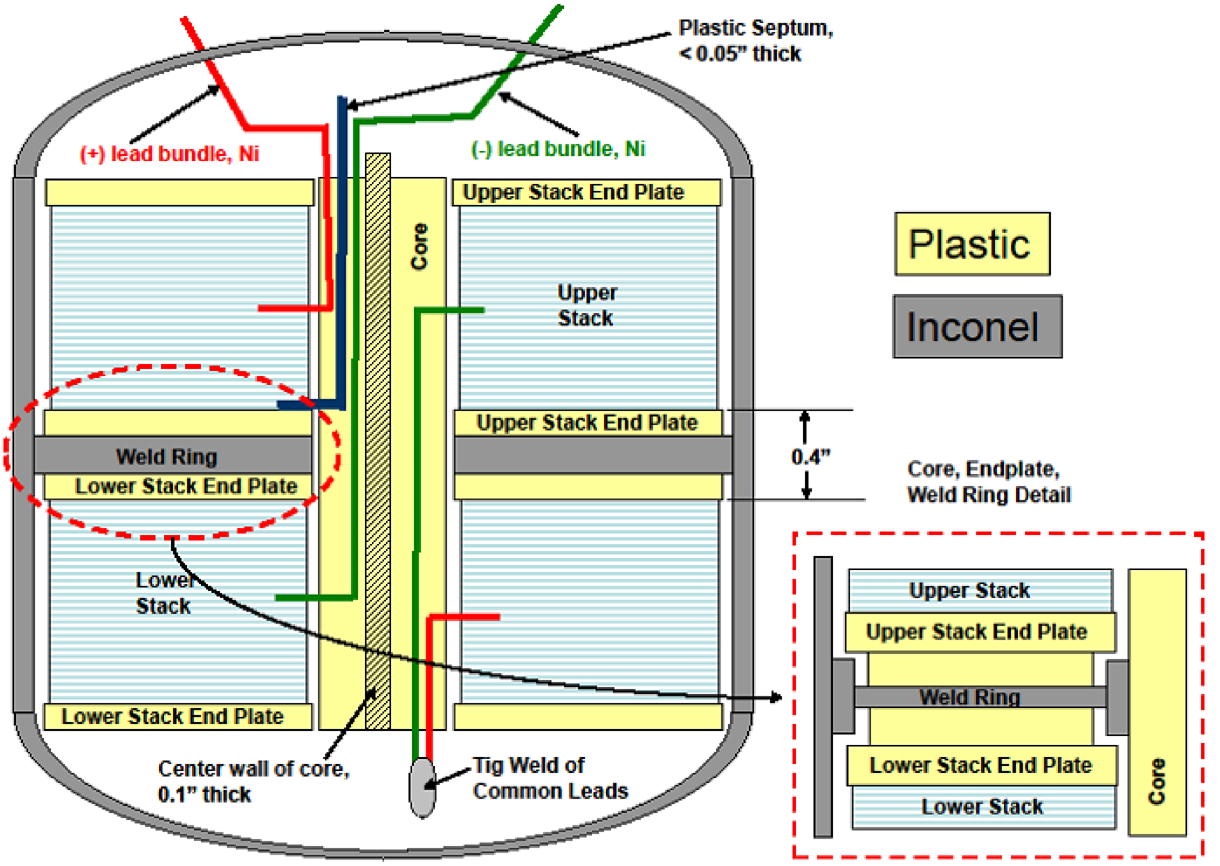

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Figure 6.2-4. Simple Diagram of NiH_2 Common Pressure Vessel Design

As depicted in the figure, the CPV design incorporates two series connected NiH_2 cell stacks into a single Inconel™ 718 pressure vessel with a non-catalyzed wall wick on its interior surface in the vicinity of the cell stacks. The cell stacks are physically separated by end plates and a single weld ring. Plate leads from each cell are connected in parallel with the negative stack lead in the upper cell connected to the positive stack lead in the bottom cell. The electrode stacks are comprised of slurry positives electrodes separated from the negative electrodes by two layers of ZIRCAR separator material. The electrolyte is a solution of deionized water and potassium hydroxide (KOH) mixed at concentration of 31 percent by weight. The support structures (endplates and core) for the electrode stacks are polysulphone plastic.

7.0 Test Data and Analysis Results

7.1 Assessment Testing and Modeling Approach

Availability of the WMAP flight spare battery and HST (spare and returned) battery cells for testing allowed the PRT to attempt to simulate battery performance both prior to, and on-orbit, and to conduct a simple evaluation of expected cell performance parameters after long duration usage. Long-term testing was obviously not considered a viable option with the flight spare battery given the desired response time to the request. The WMAP project desired a rapid turnaround to arrest the degradation rate, if possible, and meet current mission extension through August 2010, so the focus was on rapidly determining adequate test parameters to maximize chances of obtaining relevant results capable of helping determine the cause and potential solutions to battery performance issues.

Initial review of the WMAP flight battery acceptance data (provided for reference in Appendix C) indicated the battery capacity performance and charge retention results prior to launch were nominal in nearly all respects. Charge retention testing performed at GSFC after delivery of the battery from the vendor indicated a charge retention value of 90 percent of measured capacity. Given the measured capacity of the battery (27.9 ampere-hours) and retained value after 72 hours measured at 25.2 ampere-hours, these values would generally indicate a self-discharge rate of approximately 37.5 mA while operating at +10 degrees C and in a fully charged state (self discharge rate can be estimated by dividing the measured capacity change by the elapsed time, or 2.7 ampere-hrs/72 hours = 0.0375 amperes). Values of 80 percent, or greater, retained capacity after 72 hours on open circuit are typically considered acceptable for NiH_2 battery tests of this nature. This value was identified to be important in evaluating the operating parameters on-orbit as the initial exhibited V/T clamp trickle charge rate was measured at roughly 5-10 milliamps up to the point of the first cell collapse event, which occurred about 6 months after launch.

In addition to the planned testing for this assessment, modeling of expected on-orbit cell capacity was also planned based on available mission parameters. This modeling utilized accepted design and performance characteristics based on historical experience and electrochemistry characteristics and was intended to provide a check on performance parameters being used by the mission and in testing. The general expected model behavior of the WMAP battery given the equivalent mission input parameters for charge current and temperature is provided in Figure 7.1-1.

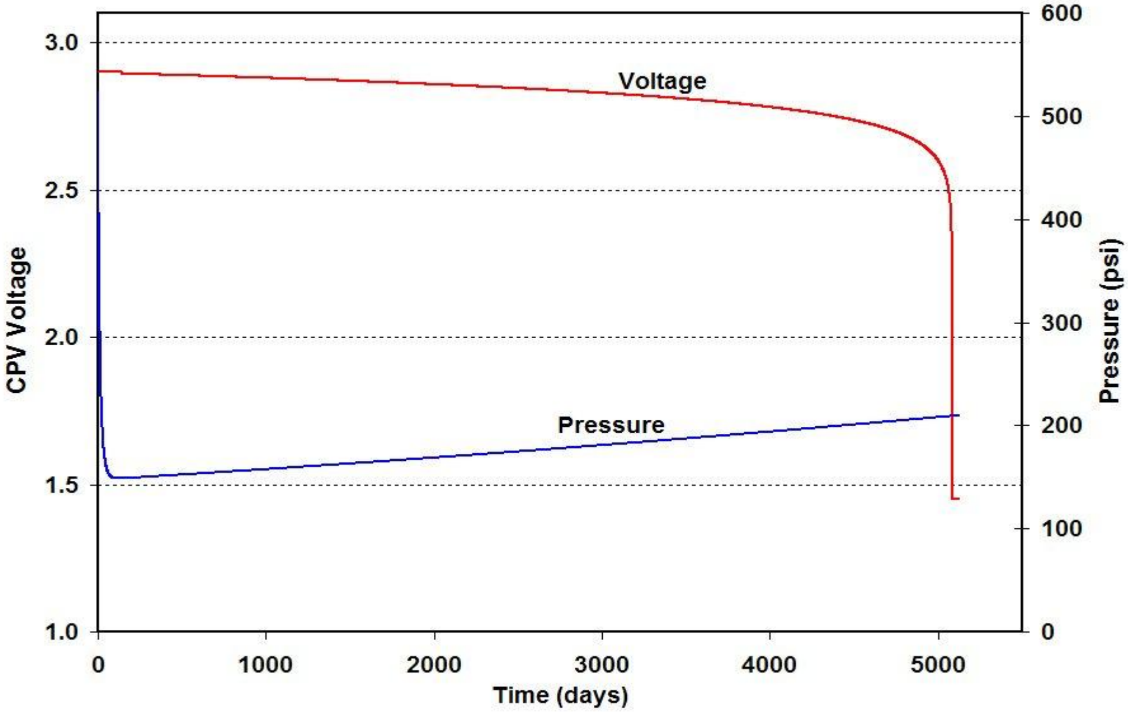


Figure 7.1-1. Modeling of NiH_2 Cell Behavior Using Low Trickle Charge Rate (Zimmerman)

Of note for the modeling results performed:

- Modeling based on previously developed IPV 23 ampere-hour cell model.
- Cell in model initially at 80 percent SOC, which would be comparable to launch/on-orbit condition experienced by WMAP.
- Model included a drop to about 10 percent SOC in 6 months assuming capacity walk-down due to operation using a V/T clamp level insufficient to maintain full charge.
- Thereafter, model SOC response dropped slowly over the next 13+ years, while pressure slowly increased.

As indicated in the model, as pressure increased, the self-discharge rate also increased. At 5080 days (or 13.92 years), the self-discharge rate finally exceeded the modeled trickle charge rate of 10 mA, ultimately resulting in cell voltage collapse. Based on historical testing and experience, this is expected NiH_2 cell behavior. It is noteworthy that the model simulation was built upon two IPV cells and does not accommodate any potential parasitic chemical or electrical reactions that might be unique to CPV cells. This modeling approach was adopted due to the absence of any equivalent CPV model being available and was intended to provide a baseline behavior to compare actual test results against.

Given the general experience of the PRT, significant undercharging was readily identified almost immediately and this was noted from the provided telemetry data indicating only 10 milliamperes was required to maintain the commanded V/T clamp voltage, an unexpectedly low value based on the extensive experience of the team members. In addition to the modeling effort, a preliminary battery test plan was developed to focus on the apparent undercharging being performed by the on-orbit system. The test plan conceived by the PRT was an attempt to specifically mimic, as close as possible, the on-orbit conditions experienced by the flight battery, but to also attempt to accelerate any possible reactions to significant undercharging. The preliminary test plan used for the investigation is provided for reference in Appendix B.

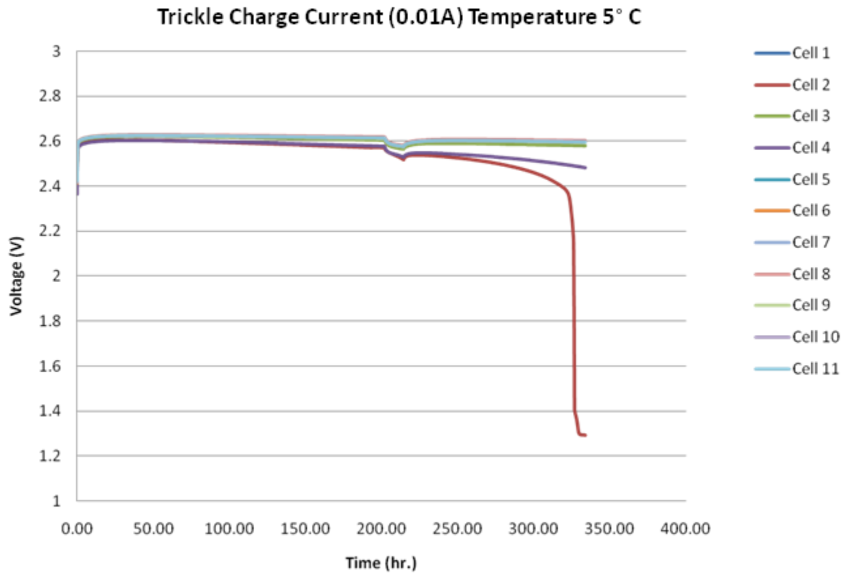
All significant flight battery test results developed during the assessment are provided in Appendix C.

7.2 Summary of Test Results

The WMAP flight spare (test) battery was subjected to simulated conditions similar to that experienced on-orbit by the flight battery. There was capacity loss experienced during testing which supported the theory of undercharging occurring over the mission timeframe. The trickle charge rate used in the test was nearly identical to the on-orbit value for the majority of the mission prior to August/December 2009 and the cell voltage collapse events.

During the first 2-week portion of the test (high SOC/low trickle) the WMAP flight spare (test) battery appeared to lose over 30 percent of capacity, based on pressure measurements. During the second 2-week portion of the test (low SOC/low trickle) the WMAP flight spare battery continued to lose capacity (approximately 25 percent of remaining capacity), and ultimately experienced a cell voltage collapse similar to that seen on-orbit and displayed in Figure 7.2-1.

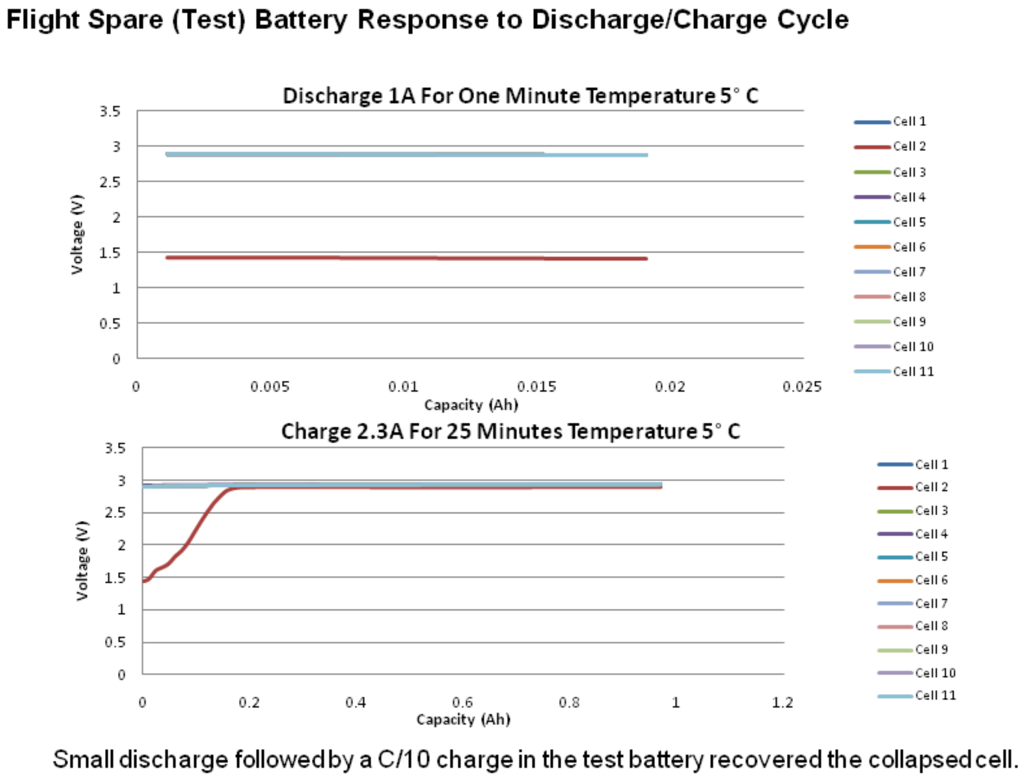
WMAP Flight Spare (Test) Battery Voltage Under Simulated On-Orbit Low Trickle Charge (C/2300) at Low SOC (at 5°C)



Simulated on-orbit conditions successfully duplicated a cell voltage collapse while using low trickle charge conditions similar to that experienced on-orbit.

Figure 7.2-1. Test Battery Voltage Collapse under Low Trickle Charge Conditions

The test battery collapsed cell was ultimately recovered using a small discharge followed by a C/200 (115 mA) charge cycle as seen in Figure 7.2-2. By comparison, HST individual pressure vessel test cells fared better during comparison testing, with only about 12 percent capacity loss at high SOC during low trickle charge and an increase in capacity (pressure) when subjected to comparable SOC, low trickle charge (plot of HST cell performance contained in Appendix).



Flight Spare (Test) Battery Response to Discharge/Charge Cycle

Small discharge followed by a C/10 charge in the test battery recovered the collapsed cell.

Figure 7.2-2. Recovery of Collapsed Cell Using Discharge/Charge Cycle

The developed theory of the higher losses within CPVs versus IPVs was generally thought to be a function of excess electrolyte forming internal bridging between cell stacks within the CPV. To confirm whether electrolyte bridging between the two stacks in a CPV cell could produce the capacity loss signatures seen in the WMAP and in the ground tests of the WMAP spare battery, a 16 Ah CPV cell has been constructed that includes an electrolyte bridge. This cell is designed to allow the ionic current between the two CPV stacks to be directly measured, thus allowing the loss current through the electrolyte bridge to be correlated with the voltage signatures as the stacks lose charge and collapse during low rate trickle charge similar to that used on WMAP. Preliminary results from this test show that lower voltage stack in the CPV self-discharges through the electrolyte bridge at a rate that is only limited by the ionic resistance of the electrolyte bridge, while the upper stack exhibits a self-discharge rate largely unaffected by the electrolyte bridge. With a ~1ohm electrolyte bridge self-discharge rates of about 1.4 A were measured for the lower stack. With an electrolyte bridge more consistent with the loss rates observed in WMAP (about 10 ohms), approximately a 125 mA loss rate was measured when the two stacks in the CPV were initially charged to ~50 percent state of charge, and the loss rate was proportional to the voltage on the lower cell. Thus, the capacity loss rate appears to be directly proportional to the ionic conductivity of the electrolyte bridge.

This loss rate is reasonably consistent with that inferred from the behavior of the cells that have collapsed in the WMAP battery. Thus, the results from this test strongly support the hypothesis that electrolyte bridges within the WMAP CPV battery could explain the observed cell voltage collapses. A report documenting these measurements is being prepared and is expected to be published by the end of August 2010.

7.3 PRT Consensus Theory for WMAP On-Orbit Battery Behavior

The PRT initially identified seven basic potential causes of the battery degradation on WMAP:

1. Manufacturing defect
2. FOD
3. External short
4. Overcharge
5. Age based capacity depletion
6. Undercharge
7. Electrolyte bridge

The subsequent evaluation of each potential cause identified is discussed in more detail below.

Manufacturing Defect

While considering the historical data available, it was noted that during the initial ground activation of the WMAP flight battery in 1999, one of the CPVs exhibited anomalous behavior (low end of charge voltage) and was ultimately removed from the battery and subjected to a DPA. The results of the DPA performed by EPT found one of the plate tabs abnormally discolored and bent within one of the cell stacks with indications it resulted in a tear of the separator material used between the positive and negative plate pairs. This area was believed to be consistent with the possible short circuit condition exhibited. The full DPA report related to this anomaly is included in Appendix E. While the issues faced by WMAP on orbit could also possibly be caused by similar defects within other CPVs, the PRT determined that this explanation was highly unlikely due to a number of factors. Foremost of which, it was believed by the PRT that in the case of the early failure, the cell quickly developed into a hard short soon after electrolyte was introduced and would be consistent with an uninsulated path between positive and negative plates within the cell stack. Any similar damage with resulting exposure such as that found in the initial anomalous cell would rapidly result in failures much sooner than the over 8 years of nominal operation exhibited by the WMAP battery. Manufacturing defects were subsequently ruled out as a likely cause.

FOD

The possibility of FOD was also initially considered as a cause for the failures experienced by the WMAP battery. Using the extensive experience base of the PRT, this approach was also discounted early in the investigation due to a number of factors including the highly unlikely probability that multiple cells would experience FOD-related short circuits in a very short period of elapsed time and because of the extended nominal operation period prior to the rapid succession of cell collapse events. Again, the PRT determined FOD was not a probable cause for the on orbit WMAP issues.

External Short

The PRT examined the available data and determined an external short was also an unlikely cause of the anomalous WMAP behavior primarily because the events documented to date occur in a random pattern throughout the battery and, for any given event, only one of the two internal cells in a given CPV are noted to collapse. If an external short was the root cause of the problems exhibited, voltage collapse events would have to be related to specific two cell events (entire CPV) or affect more than one CPV. The two internal cell stacks within each CPV are designed to be electrically isolated to external short circuit conditions via two separate insulation layers incorporated in the WMAP battery design. Subsequently, external shorts were also excluded from further consideration in this assessment.

Overcharge

Overcharge was almost immediately removed from consideration as a probable cause given the available information. Normally overcharge would be a concern for cell degradation as a result of the damage that can result due to the effects of undesirable oxygen generation and subsequent rapid recombination with the hydrogen present within a cell, or CPV. The elimination of overcharge from consideration was primarily a result of the observed relatively low voltage clamp imposed for most of the mission (approximately 1.4V/cell) as well as the lack of excessive heat generated by the battery due to charging (the WMAP mission battery heater was enabled and operating for most of the mission up to the point in time of the recent cell voltage collapse events). Given the small thermal dissipation capability of the WMAP radiator, overcharge conditions would have most likely resulted in uncontrollable thermal runaway, which did not occur.

Age Based Capacity Depletion

NiH_2 cells in operation, like all chemistry based battery cells, will eventually reach a condition of no longer being able to retain useable capacity. Based on historical and test data compiled for many programs, the lifetime expectancy will vary significantly depending on multiple factors such as operating temperature, number of charge discharge cycles, cycle depth of discharge, etc. In the case of WMAP the related factors that typically affect lifetime, other than calendar life, were effectively benign since there were no appreciable cycles ever imposed on the WMAP battery and the temperature was maintained well within acceptable ranges throughout the mission. Given the mission operating conditions, the battery in general would actually have been expected to perform adequately for significantly longer than the elapsed time it has been in use, barring any other fundamental internal CPV issues. The end of life age related failure characteristics for NiH_2 cells also typically would be more evident in the inability to provide discharge current without rapidly collapsing in voltage but, would normally retain an equally rapid nominal/full charge voltage characteristic. WMAP has not shown any indication of these characteristics and thus age based capacity depletion was eliminated from consideration by the PRT.

Undercharge

The PRT found there was generally insufficient information available to determine actual battery state of charge condition (only full and half battery voltages and temperature). After excluding singular unique possibilities for the cause of the anomalous behavior, it was evident that given the low V/T clamp value (V/T level 3) selected for maintaining charge on orbit, inadequate trickle charge current likely led to capacity walk-down and eventual cell voltage collapses. The primary indication that the cells were undercharged was the observed telemetry information showing that the trickle charge current was only approximately 5 mA for the first 6 months of the mission. After the initial cell voltage collapse event and readjustment of the V/T clamp to V/T level 0, the trickle charge current remained low and only in the range of 8 mA. An examination of the acceptance data for the WMAP flight battery indicated high SOC self-discharge characteristics alone would account for at least 4 times the observed 8 mA trickle charge current value, at a minimum. The PRT determined during testing of the flight spare battery that the observed and unexplained capacity loss mechanisms within CPV cells did allow for maintaining the commanded voltage clamp of the battery to be retained while experiencing significant voltage divergence of individual cells/CPVs (some CPVs rising in voltage to counteract other cells dropping in voltage but retaining an overall voltage clamp). The phenomenon of voltage divergence between the two cell stacks within any CPV would also be possible if the self discharge characteristics were different, as well.

Electrolyte Bridging

The PRT further concluded based on experience that if there is an internal potential difference between the cell stacks in a CPV, the induced voltage could result in electrolyte migration along conductive leads and also assist in creating favorable conditions for forming an ionic bridge between the cells stacks. Again, CPVs are unique among NiH2 battery cell designs in that they contain two individual cell stacks within a single pressure vessel that permits this transport mechanism between the two cells. This condition of electrolyte bridging between the two stacks within a CPV was uniquely identified as possibly providing an explanation of all of the observed characteristics displayed and subsequently was considered the most probable cause for the unexpectedly higher internal losses linked with all observed cell collapse and recovery attempt events. The available data again reveals that with each event only one of the two cell stacks in a CPV is involved. It was generally theorized that the type of electrolyte bridging identified could possibly occur on the cell wall, across the weld ring, or along the electrical connection between stacks and, generally speaking, it is also believed that the longer the differential potential condition exists within the CPV, up to the point of limiting the available free electrolyte, the more complete the electrolyte bridge will be and the more difficult it would be to eliminate without the ability to fully recondition the cells. Also supporting the theory of electrolyte bridging is the observation that following the collapses, cells were observed to have significantly reduced capability to retain (or increase) capacity. The consequence is the cell charge acceptance is compromised and subsequent cell collapse is more probable.

Most likely locations for the possible bridging causing anomalous WMAP battery behavior are shown in Figure 7.3-1.

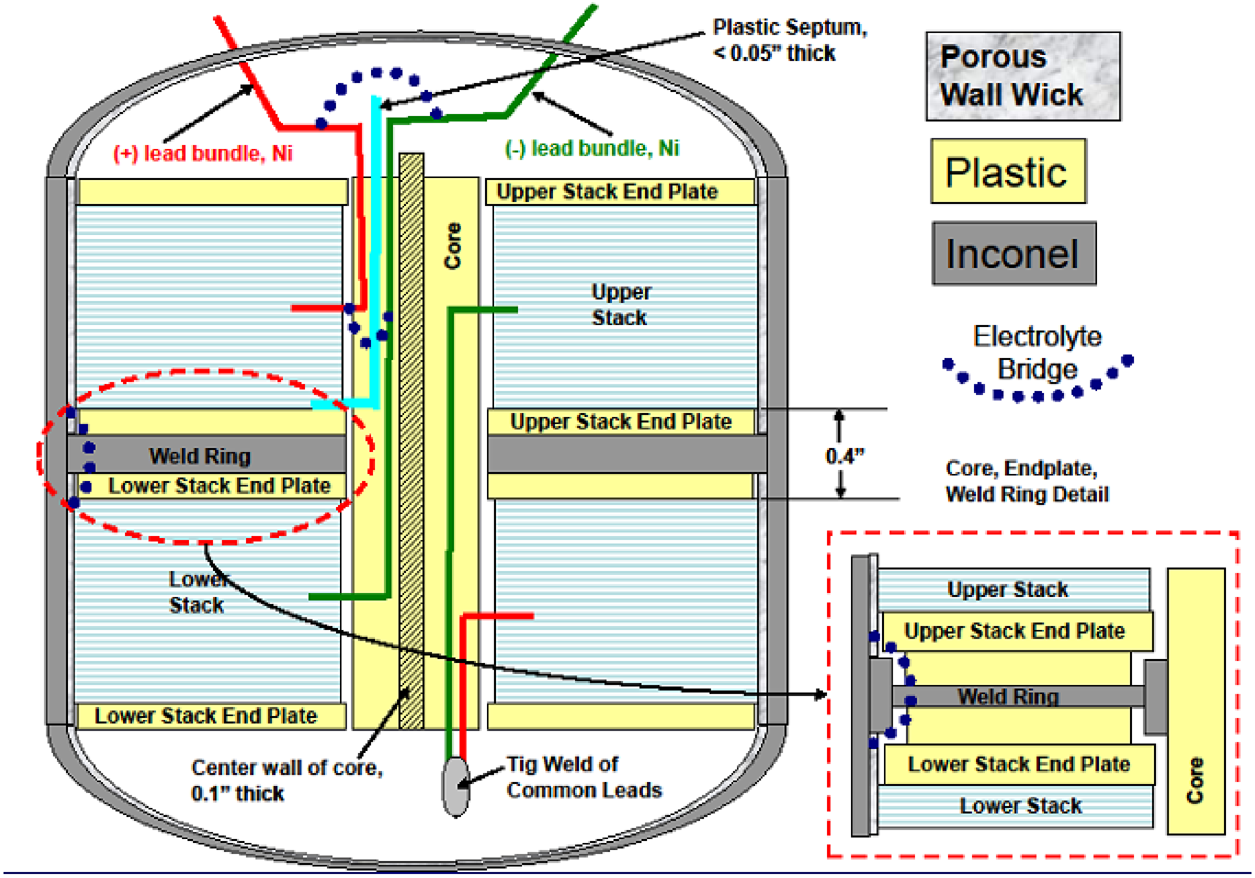


Figure 7.3-1. PRT Consensus Theory of Cell Anomaly

7.4 Possible Options Available to Retain Battery Health

Given constraints related to on-orbit WMAP operations, there are no readily known means identified to characterize electrolyte bridging as theorized. Full reconditioning of the battery, in the hopes of reabsorbing some of the bridging electrolyte, may help. However, the WMAP mission would be unable to function with the battery completely discharged during full reconditioning. One alternative, if possible, would be partial reconditioning assuming sufficient voltage headroom is available to maintain adequate power supply voltage to the WMAP spacecraft loads. The problem remains, however, that little knowledge relevant to electrolyte bridging in the WMAP batteries is available. It is known, however, that CPVs that have been left in open circuit condition, for sufficient periods of time (COMSAT experience indicates time necessary for meaningful reabsorbtion of electrolyte would be on the order of weeks), tend to reabsorb free electrolyte. Again, given the fragile nature exhibited by the WMAP on-orbit battery, this approach may not be feasible without risking further collapse of the battery voltage to an unacceptable level prior to reaching any meaningful improvement characteristics. Complicating this potential mitigation technique is the physical inability to obtain a true open circuit condition as the battery is incapable of being removed from the spacecraft electrical bus. This approach, if adopted, would require the spacecraft be configured to set a zero charge current parameter for commanded trickle charge and then operate in more of a quasi-open circuit condition.

Monitoring and trending available battery parameters should continue regardless to detect any behavior suggesting impending cell collapse, and adopting a charge regimen designed to maintain overall battery health should be performed, as necessary. One potential recommendation identified during the investigation would include periodically charging at a high-as-possible rate to help promote capacity improvement in suspect cells while maintaining the temperature below +10°C. The theory for this recommendation is that the cells will operate more efficiently and be more receptive of charge input; however, the limitations associated with the battery thermal dissipation capability inhibit significant input prior to reaching recommended upper limit temperatures.

It is generally accepted that electrolyte can creep across metal surfaces when the metal is held below its point of zero charge. In alkaline battery cells, this condition occurs on wires connected to the negative cell terminal if the cell voltage is allowed to collapse. Significant electrolyte creep typically requires days to weeks. Although electrolyte creep has not been formally demonstrated to occur in a CPV test, under low-voltage conditions, theory suggests it is critical to avoid allowing any remaining non-affected cells to collapse in voltage in order to reduce the likelihood of additional electrolyte bridging. Based on the theory and on-orbit experience to date, cells/CPVs that have experienced collapse are believed to be the most at risk for re-collapsing. It is thought that the longer the time cells/CPVs remain in a collapsed state, the more they are at risk of re-collapse. Because significant electrolyte creep can occur on the time scale of weeks, recovery of cells that remain collapsed for a number of weeks or longer is likely to be difficult.

If the initial cell collapsed event observed in 2001 was also a result of the undercharge condition, and not a result of FOD or manufacturing defect as considered at the time of the event, this may help explain the persistent inability to recover the cell capacity characteristics regardless of the number of charge cycles attempted.

Keeping with accepted practice for maintaining the health of NiH_2 battery cells, WMAP battery temperature should be maintained between 0 and +5°C whenever possible to avoid risk of potential undesirable high temperature H_2/O_2 recombination or low temperature freezing effects, with the possible exception of excursions to a maximum of +10°C as required for charging. While normally the KOH electrolyte is not susceptible to freezing at temperatures above -20°C, the risk of damage due to freezing is possible if water is present at 0°C or lower. Given the unknowns surrounding the actual condition of the WMAP battery, water precipitation as opposed to uniform KOH electrolyte is considered a possibility and this is why favorable thermal conditions should be retained.

Gradually increasing trickle charge current as required to maintain voltage, may also provide benefits to battery performance while maintaining battery temperature below +10°C. An increased charge current may exceed the displayed high self-discharge current and allow overall increase in charge capacity; however, increased temperature of the battery will usually also equate to increased self-discharge characteristics. Ideally, an optimized condition may exist that minimizes (or eliminates) the net self-discharge loss of capacity within the battery. However, this condition has not been found based on the observed behavior of the WMAP battery to date and would likely require more extensive on-orbit testing of various trickle charge current commanded values to determine any local minimum self discharge characteristics versus temperature and charge current effects.

There are significant concerns, implications, and constraints that are of interest to the PRT in attempting to stem the WMAP performance degradation that must be weighed against any potential actions implemented to combat the voltage decay experienced. Of most concern is the apparent net thermal response of the battery due to either increased self-discharge as a result of internal degradation or increased commanded trickle charge rates. If the cell self-discharge rates are actually increasing with time as a result of whatever internal problem is occurring then, when coupled with an increased battery temperature, the observed losses would be expected to increase. In particular, this concern poses a dilemma as the temperature of the battery will increase due to commanded increased trickle charge rates adopted to counteract the apparent increased voltage loss mechanism. Because of the increased inefficiency of charge acceptance, the thermal response could ultimately result in a runaway condition. This thermal runaway would be seen as being caused specifically by the self induced battery cell discharge rate increasing as the temperature increases and could reach a point at which the battery can no longer be maintained within acceptable thermal limits. Another concern exists solely because of the lack of viable options available to effect any significant operating condition improvement. Given the decrease in WMAP battery voltage experienced to date, there is obviously little to no margin available for any normal or mini reconditioning. Coupled with the thermal concern identified earlier, there is no effective safe means for overcharging the battery in hopes of stemming the voltage decay.

Finally there is a possibility that the degradation is being accelerated as a result of what would otherwise be considered “normal” or “healthy” actions being implemented to date in order to address the degradation. Lacking any definitive insight into the cause of the problems being experienced and not having the luxury of time to more effectively determine the cause through testing has resulted in only the ability to speculate on the root cause and thus only be able to provide general guidelines for healthy actions to address the issue or issues. Compounding the concern is the lack of more definitive diagnostic information from the on-orbit battery, such as individual CPV voltages or internal CPV pressures.

In any event, based on the data available and testing performed using the test battery and HST cells, the PRT was able to develop general findings, observations, and NESC recommendations that are listed in Section 8.0.

7.5 Implications for Other Missions

While WMAP operates in a full sun condition at L-2, the investigation may provide some beneficial insight for other missions utilizing CPV battery cells such as CloudSat, SORCE, STEREO, and MESSENGER. In the case of CloudSat, the mission is a low Earth orbit (LEO) satellite that experiences approximately 16 charge/discharge cycles on a daily basis (98.2 degree inclination polar orbit). CloudSat was launched in April 2006 and in December 2009 encountered a battery anomaly. This issue was apparently related to under voltage and subsequently identified one CPV that was experiencing a similar cell voltage collapse believed to be like that encountered by WMAP. While the PRT did not focus on the apparent failure encountered on CloudSat, there may be some performance similarities to the anomaly on CloudSat when compared to WMAP. However, there are also significant differences which might tend to indicate the problems experienced are different. Of note regarding the differences are the dynamic operating conditions associated with a LEO mission as opposed to the relatively static conditions related to an L-2 orbit. With the WMAP theory of electrolyte bridging being caused by a driving potential difference within the CPV, the electrolyte migration could theoretically continue to grow because the potential conditions remained relatively static. When possibly coupled with severe undercharge conditions, the WMAP experience indicates this condition was consistent within multiple cells as the WMAP events indicate only a relatively short time between nearly identical collapse events.

In the case of CloudSat the anomalous behavior has thus far been isolated to only one CPV (after approximately 3 ½ years in orbit) and would typically be thought to be more likely indicative of a potential manufacturing defect (i.e., FOD or other internal damage similar to the WMAP failure encountered during activation) ultimately causing a soft internal short circuiting of the affected cell. The fact that the electrical current (and driving potential) is reversed frequently due to the LEO demands would also tend to negate a common failure mechanism between CloudSat and WMAP, although it cannot be completely discounted because the phenomena of the WMAP will not likely ever be completely understood.

The SORCE satellite also has operated a CPV battery in a LEO, and has been in operation for nearly 8 years. This satellite also exposes the battery of 11 CPV cells to dynamic charge/discharge cycling, similar to CloudSat. In the past year, three of the CPV cells in the SORCE battery have shown evidence of significant voltage degradation. It is possible that this voltage degradation, which has also been seen in recent analysis of CPV ground test data, is related to the electrolyte bridging phenomenon. Because SORCE has the charge control and thermal dissipation capability to fully charge the battery every orbit, the effects of the electrolyte bridging to deplete some battery cells can be overcome. However, it is likely that long-term degradation of the stacks in these CPV cells also occurs in response to the transfer of electrolyte and oxygen gas between the two stacks in the CPV cell.

Regarding STEREO and MESSENGER, while the vast majority of orbital conditions experienced to date are similar, STEREO and MESSENGER both adopted a significantly higher fixed trickle charge rates to maintain the batteries during the long solstice operating conditions. The conditions related to the performance to date for STEREO and MESSENGER would indicate very stable performance and no infant mortality type anomalies due to undercharging or manufacturing defects as experienced with WMAP. While there is always a possibility that FOD or manufacturing defects may be present in the STEREO and MESSENGER batteries, the lack of periodic cycling would likely reduce any repetitive stress cycles and thus likely reduce the chance of migration of FOD and soft short circuit conditions as compared to the possible case of the anomaly with CloudSat. In the longer term, however, it is still possible that STEREO and/or MESSENGER may experience a potential driven electrolyte bridging issue, particularly if any internal potential driven mechanisms exist and are ultimately the root cause for all observed WMAP cell collapse events. It would be difficult to determine with accuracy whether the WMAP type threat exists for STEREO and MESSENGER primarily because the experiences in charge maintenance are significantly different and, without long term testing of CPV cells operating under both conditions, the effects of the differences may be sufficient to alleviate the failure possibility.

8.0 Findings, Observations, and NESC Recommendations

8.1 Findings

The following findings were identified:

F-1. The observed WMAP flight battery on-orbit behavior with the WMAP flight battery was atypical for IPV NiH_2 cells and appears to be unique in nature for CPV cells.

F-2. Battery voltage reductions of 1.4V are consistent with the collapse of an individual cell due to complete self-discharge.

F-3. The collapsed cells do not accept charge efficiently after their collapse. Most of the recharge energy is dissipated as heat and little was converted into stored energy.

F-4. The trickle charge resulting from the chosen V/T level of 1.4V per cell was insufficient to maintain a consistent SOC beyond 8 years of life. Based on standard NiH_2 battery test experience and typical recommendations from the battery vendor (EaglePicher Technologies), the WMAP CPV based battery capacity was insufficiently maintained on-orbit using a temperature compensated voltage (V/T) charge maintenance at the level implemented.

F-5. The prelaunch decision to eliminate on-orbit pressure measurements using the available strain gage cells severely limited the ability to determine if the battery was being properly maintained.

F-6. The WMAP battery thermal design severely limits the ability to properly rebalance or recharge cells after discharge has occurred and the cells do not accept recharge (radiator designed for nominal rejection of only 5 watts which limits prolonged charging above trickle charge rate due to potential thermal runaway).

F-7. Test results indicate that IPV cells as designed are not as susceptible to capacity losses attributed to electrolyte bridging.

F-8. With two series connected cell stacks within a single pressure vessel, charge transport mechanisms can exist between the cells potentially degrading performance in one, or both, cell stacks.

8.2 Observations

The following observations were identified:

O-1. Based on battery acceptance data, the minimum trickle charge rate at beginning of life (BOL) required to maintain battery capacity should have been at least sufficient to replenish observed self-discharge rate of 38 mA.

- Standard practice is to use a trickle charge rate at least double the expected self-discharge rate to assure outlying cells are sufficiently charged.
- Recommended battery vendor (EaglePicher) practice is to use C/200 to C/100 trickle charge rates to maintain battery performance.

O-2. Based on available data, the observed on-orbit phenomenon fits well with the theory that electrolyte bridging between cell stacks within some of the CPVs, coupled with electrolyte loss, is causing voltage and capacity decay.

O-3. Voltage divergence was observed for two of the CPVs when the WMAP test battery was changed to constant potential charge (V/T clamp).

- Increasing divergence would indicate relative CPV self-discharge characteristics are significantly different when maintained under a temperature compensated constant voltage clamp.

O-4. A definite performance difference exists between the WMAP (CPV) and HST (IPV) test cells.

O-5. Based on test results using the WMAP test battery, increasing the trickle charge rate (without high rate charging) ultimately resulted in a larger voltage divergence between the highest and lowest voltage CPVs.

- Prior to increasing the trickle charge rate, dV was ~1.294V and grew to ~1.315V after increasing the trickle charge rate to 115 mA.

O-6. Based on available data and test results, periodic high current charging provides benefits to maintaining cell capacity and voltage and coupled with a discharge cycle may also improve performance.

- Test battery performance appears to be returning to near nominal after discharge/charge cycle.

O-7. Given the electrical architecture of the WMAP power system, the battery cannot be placed on true open circuit, but can be commanded to zero charge current, if necessary (resulting charge/discharge current controlled by accuracy of control loop) to achieve a quasi-open circuit operation.

O-8. Electrolyte bridging may be accelerated due to an electrolyte concentration difference between the two stacks. As one of the two stacks slowly discharges due to a small ionic current flow the electrolyte concentration increases thereby providing a possible mechanism for continuing electrolyte coupling.

8.3 NESC Recommendations

The NESC recommendations, directed to the WMAP project, are based on the likelihood that an electrolyte bridge exists between the two cells of a CPV:

R-1. Maintain a minimum trickle on the WMAP NiH_2 battery at a rate of at least C/200, independent of the voltage clamp setting. ***(F-4, O-1)***

R-2 Periodically charge the WMAP NiH_2 battery to assure the remaining active cells do not operate close to a fully discharged state. ***(F-2, F-3, F-4, O-3, O-6)***

- Including current pulsing if necessary
- Battery temperature should be maintained below +10°C at all times.

R-3 Increase the trickle charge rate incrementally, if needed, to maintain voltage stability and performance up to the maximum recommended battery temperature of +10°C. ***(F-3, F-6, O-3, O-8)***

R-4 Perform discharge/charge cycling, or a period of open-circuit followed by charge, at least once to redistribute electrolyte and to characterize the response. ***(F-6, F-8, O-7, O-8)***

- Precautions should be taken to assure no other CPV cells collapse in voltage during the discharge by discontinuing discharge as soon as battery indicates a sharp drop in voltage consistent with one or more cells.

- The net ampere-hour charge should always exceed the ampere-hour net discharge in order to assure battery cells are not inadvertently undercharged prior to the next contact. At a minimum at least a 1.1 recharge ratio should be used, preferably more.
- Close monitoring of voltage and temperature, particularly during the discharge, should be performed.

9.0 Alternate Viewpoints

There were no alternate viewpoints identified during the course of this assessment by the PRT.

10.0 Other Deliverables

A formal list of recommendations will be submitted to the WMAP project/stakeholder to assist in extending the on-orbit life of the WMAP battery. A test report detailing representative electrical stress test and/or DPA of WMAP spare flight cell performed during the assessment will also be provided. Upon completion of the written final NESC report, this assessment will be considered complete.

11.0 Lessons Learned

LL-1. Calibrated pressure measurements should always be included in the design and operation of missions utilizing NiH_2 batteries in order to provide adequate information regarding actual state of charge (pressure measurements are the only means to definitively determine relative state of charge).

LL-2. The basic design characteristics do not inhibit the possibility of electrolyte bridging between the two stacks in CPV NiH_2 cells, which can significantly increase the charge losses in these cells compared to traditional IPV NiH_2 cells. This interaction can cause abnormal degradation of CPV cells for some operating conditions. Because of the additional charge losses, it should be expected that CPV cells in other satellites that have no capability for rest events like complete discharge may require more recharge than do IPV cells in the same environment. This effect is expected to be greatest in satellites that have no capability for rest events like complete discharge and utilize low battery recharge rates and spend most of their time in full sun, but is also expected to be noticeable in low-earth orbiting satellites. For this reason, additional efforts to insure well balanced cell stacks within a CPV should be a paramount concern during cell screening.

LL-3. Low rate trickle charge (below C/250) for extended periods does not maintain the SOC of the CPV cells including the battery voltage clamp procedure.

12.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established by the investigating authority.
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.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	An action identified by the NESC 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.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.

13.0 Acronyms List

^{O}C	degrees Celsius
A	amperes
ACE	Attitude Control Electronics
Ah	ampere-hours
BOL	beginning of life
C	nameplate capacity of battery
C&DH	command and data handling unit
CCR	contract change request
CDR	Critical Design Review
CPV	common pressure vessel
DC/DC	direct current to direct current
DET	direct energy transfer
DPA	destructive physical analysis
EMI	electromagnetic interference
EOC	end of charge
EOL	end of life
EPT	EaglePicher Technologies
FOD	foreign object or debris
GaAs	gallium arsenide
GEVS	Goddard Environment Verification System
GSFC	Goddard Space Flight Center
H/W	Hardware
Hr	hour
HST	Hubble Space Telescope
I&T	integration and test
I/F	interface
IPV	individual pressure vessel
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KOH	potassium hydroxide (electrolyte)
L-2	libration point 2
LaRC	Langley Research Center
LEO	low Earth orbit
mA	milli-amperes
MAP	Microwave Anisotropy Probe
MESSENGER	Mercury Surface, Space Environment, Geochemistry and Ranging
MTSO	Management Technical Support Office
NESC	NASA Engineering and Safety Center
NiCd	nickel cadmium

NiH_2	nickel-hydrogen
NRB	NESC Review Board
NRO	National Reconnaissance Office
NSWC	Naval Surface Warfare Center
PR	problem reports
PRT	Problem Resolution Team
PSE	power system electronics
psi	pounds per square inch
RSN	remote service node
S/A	solar array
S/N	serial number
S/W	software
SG	strain gage
SOC	state-of-charge
STEREO	Solar Terrestrial Relations Observatory
TDT	Technical Discipline Team
V	voltage
V/T	temperature compensated voltage
VDC	voltage direct current
WMAP	Wilkinson Microwave Anisotropy Probe
WOA	work order authorization

Volume II: Appendices

Appendix A. WMAP Battery Status and History

The following information was provided by Mike Bay to describe the history of the WMAP battery.

- This battery is a 23 Ampere-Hours (Ah) NiH_2 battery comprising of 11 common pressure vessels (CPV) or modules. Each module has 2 cells in a common pressurized container. The battery is wired for two cell pressure telemetry points, five temperature sensors (4 thermistors and 1 PRT) (one thermistor for GSE J3 test connector), pack voltages and individual cell voltage monitoring (at J3 test connector). This battery is for a nominal 28 voltage direct current (VDC) electrical power system and weighs about 21.7 kg. The battery dimensions are 17.632 inches in length by 12.979 inches in width by 7.946 inches tall. Each cell has bypass diodes to protect the battery from any open circuit cell and the battery is equipped with a dead face relay for ground operations.
- The MAP flight spare battery is flight worthy and ready for operations with the spacecraft for integration and test (I&T). For this project, the I&T battery is also the flight spare. Lot #1 battery modules have passed MAP life test requirements.
- The flight battery build Lot #2 is presently being built with the cell modules completing activation and proceeding towards battery build for a scheduled shipment to GSFC on April 27, 2000. This cell will be DPA'ed sometime during the beginning of next year to determine the cause of the shorted cell.
- In parallel to the flight battery build a module bypass switch is being pursued to deduce weight and eliminate thermal induced restrictions if a module should have an open cell.

History

- The Specification and Statement of Work (SOW) for the MIDEX Spaceflight Battery was dated July 1997 and specified minimum requirements without specifying the type of cells or capacity requirement. The Spec and SOW was based on NiCd specification and made generic as best as possible. Two contracts were let with this Spec and SOW IMAGE and MAP. The IMAGE battery is a 21 ah NiCd battery where MAP is a 23 Ah NiH_2 battery. The IMAGE contract went to EPT in Colorado Springs and the MAP contract went to EPT in Joplin, MO. Both contracts were for two flight batteries.
- The MAP Contract started in early 1997 under contract # NAS5-97123. Contract changes for the MAP battery started on June 11, 1997 with a request for adding a bypass network. EPT responded on June 16, 1997 with a switch bypass system. A second ROM on July 2, 1997 answering some mass impact and provided a diode bypass system.
- A cell CDR was on July 24, 1997 with 17 action items. Contract Change Request (CCR) 71 added diode bypass system. PR dated August 20, 1997. Contract mod #3 dated March 3, 1997 CCR 78 added dead face relay dated July 1, 1997. PR dated June 11, 1998. Contract Mod #4 dated August 8, 1998. CCR 98 dated September 11, 1997 delayed the

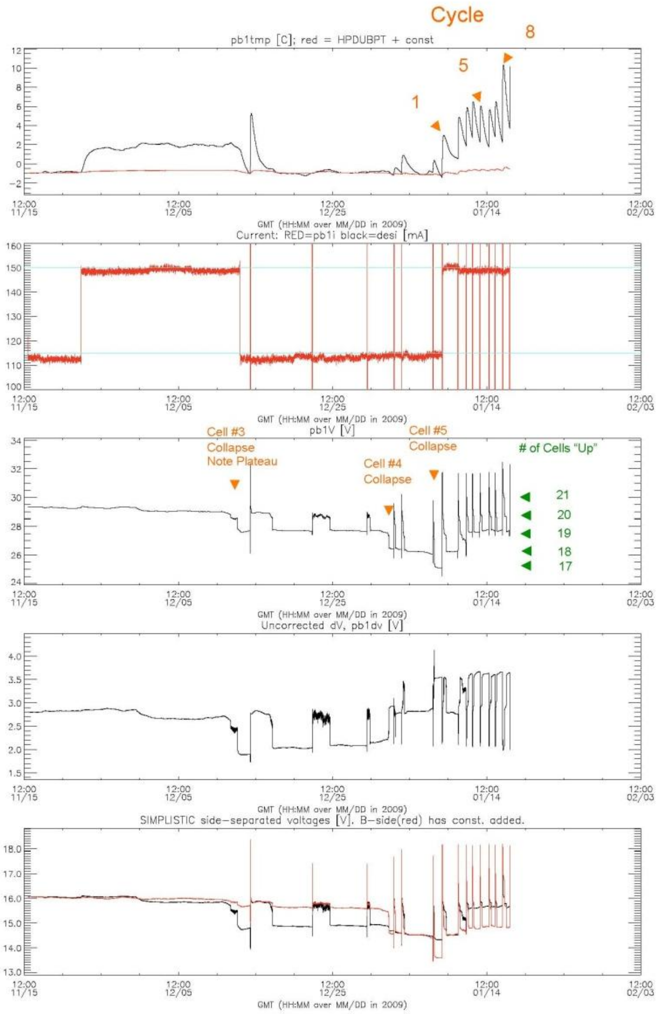
activation of the flight cells for a Flight Battery delivery date of December 1999, plus or minus 6 months. Contract modified on June 24, 1998. CCR 116 dated January 5, 1998. Change battery specification to reflect NiH2 cells with respect to 72-hr open circuit stand charge retention. PR dated xx13xx. Contract mod #1 dated April 23, 1998.

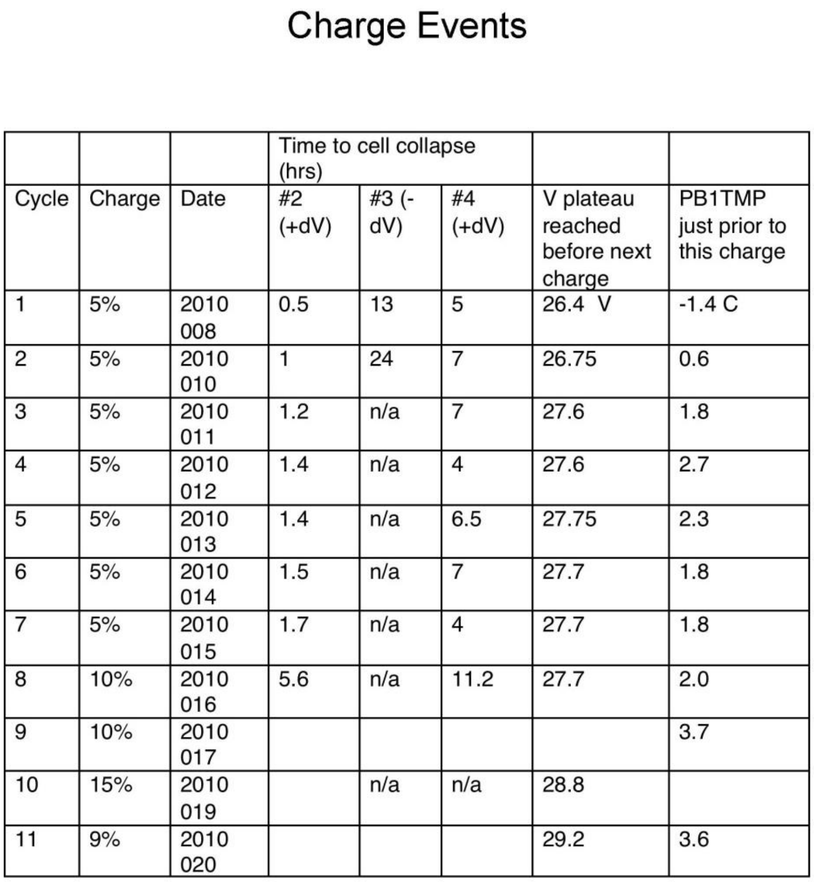
- Bob G. Beaman replaces Doris Jallice as battery engineer. This was conveyed at a meeting on January 6, 1998 with direction from John Day and Marlon Enciso, and confirmed by Doris Jallice letter dated February 18, 1998.
- Cell ATP data review and cell buy off February 18, 1998 generated 14 action items. CCR 165 MAP battery buy off waiver (#1) to change battery impedance form less than or equal to 30 milliohms to up to 0.085 ohms. And Waived battery level phenolphthalein electrolyte leak check for a hydrogen leak check in a vacuum chamber to 1 x10^-7.
- COMSAT DPA of cell S/N# 19 test and DPA, see COMSAT report RFST/98-591 dated July 17, 1998. Cell overall condition was acceptable for the MAP mission. Two areas of concern were seen: one excessive blisters on the positive plates, and that two positive plates were chipped in the inner core area where the plates are coined (possibility of causing cell shorts). Also refer to EPT response to the battery cell DPA concerns via Engineering Communication REF: 2862-ENGR- 001 dated July 7, 1998. Cell # 19 was selected for DPA due to COMSAT capacity data that showed reduction in capacity over EPT ATP data.
- CCR 152 to provide Fine Focus X-Ray for battery cell prior to DPA. Concerns with the cells due to excessive blisters. PR dated August 11, 1998. Blisters are a concern when cycles could cause rupture and a short. It was judged that the amount of blistering seen on the cells was not a concern for the MAP mission, due to its low cycling mission profile.
- A Fine Focus X-Ray was also done for the chip issue. The cell selected looked OK. EPT asserts that the chips happened when the cell was DPA’ed. The Project and Battery group feel the chips are a workmanship issue, and the vibration is a sufficient screening for this type of workmanship issue (either the particles will move out of where they can cause a short, or the cell will short).
- Both batteries have undergone vibration testing. CCR 172 change wiring and add thermistors. PR dated November 11, 1998.
- Diode board Vibe. The diode board seamed to vibrate excessively during the battery vibe test. Diode board was revibed on September 4, 1998 with the Qual battery and found to have a acceptable first moment at 59.83 Hz.
- Cell Life test. MAP first activation lot cells S/N# 15,16,28,30 and 53 were life tested at Naval Surface Warfare Center (NSWC) Crane Indiana. For more than 490 cycles to a GSFC test plan for the MAP program dated October 20, 1998. Test was successfully passed MAP mission requirements.

- MAP NiH_2 Battery Handling document dated May 1999 was approved and signed off.
- The Flight Spare Battery Buy off was on August 26, 1998 at EPT Joplin MO. An action item list with 9 items on it was generated. CCR 231 MAP Battery Buy-off Waiver #2. Waives the 1 uf capacitors find # 38. The capacitors are not flight qualified; they were changed in the flight battery. Flight Spare battery was brought into GSFC under MAP work order authorization (WOA) 379 (RTS WOA 19999030302). It arrived at GSFC on March 30, 1999 at 11:12 AM in a 50 deg F (10 deg C) refrigerated truck. This work order generated 5 problem reports (PR). All but two were resolved at GSFC and these were PR# 2 "Bypass diode board has several places where wires are very close to standoff threads/nut. Note: Wires are stacked." In order to resolve these two concerns the battery was returned to EPT on May 12, 1999 for rework. Rework was inspected and is OK.
- CCR 303 changes the battery flight operating temperature range from "0 deg C to +25 deg C in flight" to” -7 deg C to +25 deg C in flight". CCR 304 established correction to proof pressure requirements. Proof pressure requirement in the battery specification calls out that each cell to be proof pressure tested at 1.5 times the maximum expected operating pressure (MEOP). EPT set the MEOP was set too low and became a problem when during battery ATP a cell reached 929 psi. This CCR set further definitions for establishing a proof pressure based of cell activation pressure data. A new proof pressure was set at 1575 psi and flight cells were tested and passed. The cells in the flight spare battery will need a waiver by similarity to the flight cells in order to bring it to acceptance.
- CCR 251. In order to meet new thermal requirements, Longer Captive Screws were needed via CCR 251 and PR dated June 7, 1999. Blank Screws were GFEed to EPT along with a PR to cover the cost of machining the screws and providing additional battery heaters (on attached to the battery).
- Both Mike Delmont and Bob Beaman visually inspected the Flight Spare battery prior to shipment from EPT to GSFC. It arrived at GSFC for the second time on June 29, 1999 at 1.00 PM. All the PRs associated with WOA 379 were resolved. WAO 598 was established to perform the electrical incoming performance and took place without any incidents or generating any PRs. DD250 was signed on August 18, 1999 by Bob G. Beaman.
- CCR 322 The Bypass Switch. This CCR is intended as a contingency for reduced weight (2 lbs, 0.907 kg) and provide unrestricted battery operation in case one cell fails open. The latest analysis by Dan Powers dated November 15, 1999 shows high operation temperatures for the operating diodes and battery radiator with one cell open cell. This will lead to limiting battery operations if a cell fails open. We have determined the battery charging regime that will support this failure case, and plan to adopt this as our contingency plan. Therefore, CCR 322 has been disapproved on September 18, 2000.

- CCR 364 to add -20 deg C to Battery thermal vacuum test. This was based on our desire to have the battery operate nominally in –5 deg range. However, EPT and Dr. Rao did not want to test the battery to this extreme. After discussions with the Project, it was decided that the Goddard Environment Verification System (GEVS) requirement of 10 deg outside of the op range did not apply here due to the active heater control. The battery survival heater is set to –7 deg C and the flight battery has been tested to –14 deg C. During activation of the flight cells (stacks), one module (CPV) of the 21 modules in the lot was found to have a short in one of the two cells/module. The cell S/N # 34 has been fine focused x-rayed to find nothing. Upon return to EPT a capacity was run on the module. The module end of charge voltage was 1.53 volts (only one series cell voltage) and the capacity to 1 volt was 24.35 Ah (one series cell capacity). DPA of the cell found particles. This is a condition that is found by screening. It has been documented and accepted in the flight battery buyoff data. During I&T testing it was discovered that the strain gage circuitry on the flight spare battery oscillated. This condition was also observed on the flight battery in the lab, and on the qual battery at EPT.
- A repair of the circuitry was not feasible given the schedule, and the magnitude of the effort. CCR 524 documents the decision to baseline the strain gage circuitry off for launch and operations. All parties concurred with this decision. Current Status (January 15, 2001). All issues with the cell lot, qual battery, I&T battery and flight battery have been documented and dispositioned. We will see adequate test time with the I&T and flight batteries in operational configuration prior to launch. The Power Branch feels that the flight battery is flight-worthy for MAP, and the Project concurs.

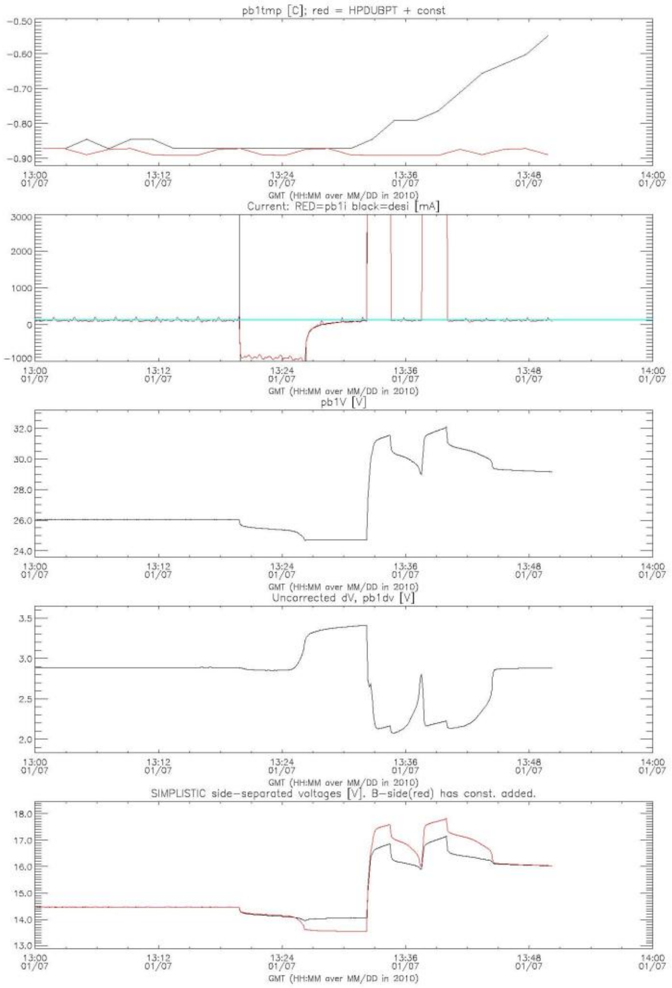
Battery Cycle History



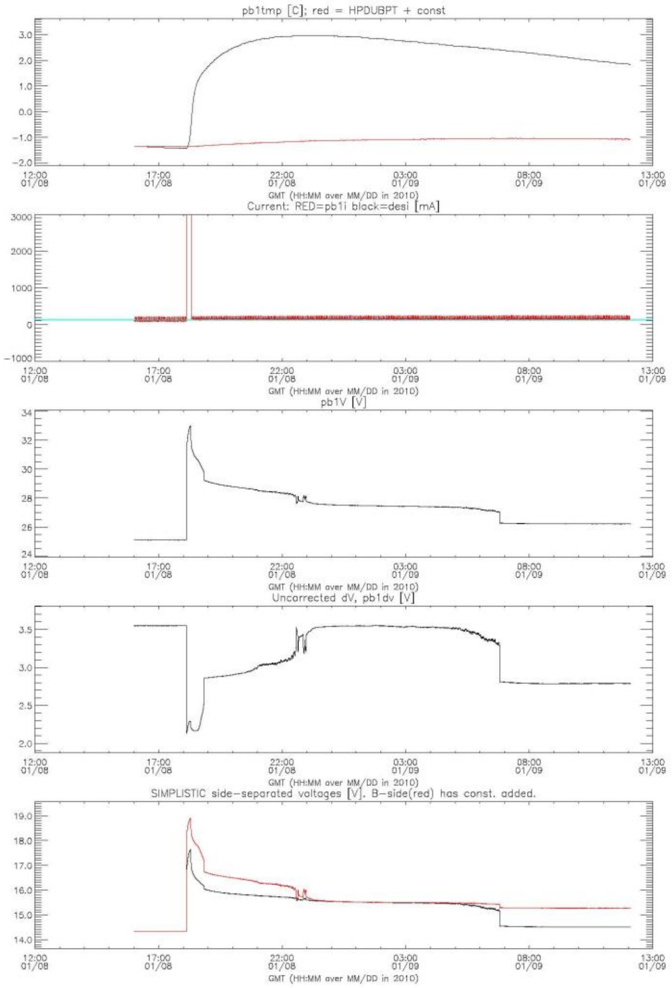


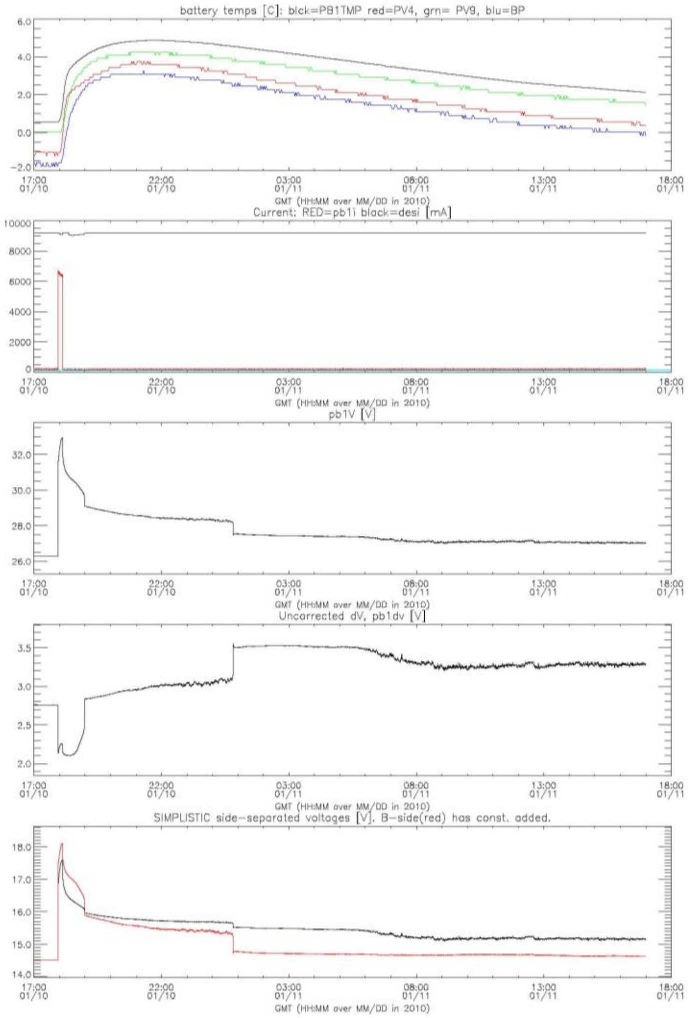
Charge Events

			Time to cell collapse (hrs)				
Cycle	Charge	Date	#2 (+dV)	#3 (-dV)	#4 (+dV)	V plateau reached before next charge	PB1TMP just prior to this charge
1	5%	2010 008	0.5	13	5	26.4 V	-1.4 C
2	5%	2010 010	1	24	7	26.75	0.6
3	5%	2010 011	1.2	n/a	7	27.6	1.8
4	5%	2010 012	1.4	n/a	4	27.6	2.7
5	5%	2010 013	1.4	n/a	6.5	27.75	2.3
6	5%	2010 014	1.5	n/a	7	27.7	1.8
7	5%	2010 015	1.7	n/a	4	27.7	1.8
8	10%	2010 016	5.6	n/a	11.2	27.7	2.0
9	10%	2010 017					3.7
10	15%	2010 019		n/a	n/a	28.8	
11	9%	2010 020				29.2	3.6

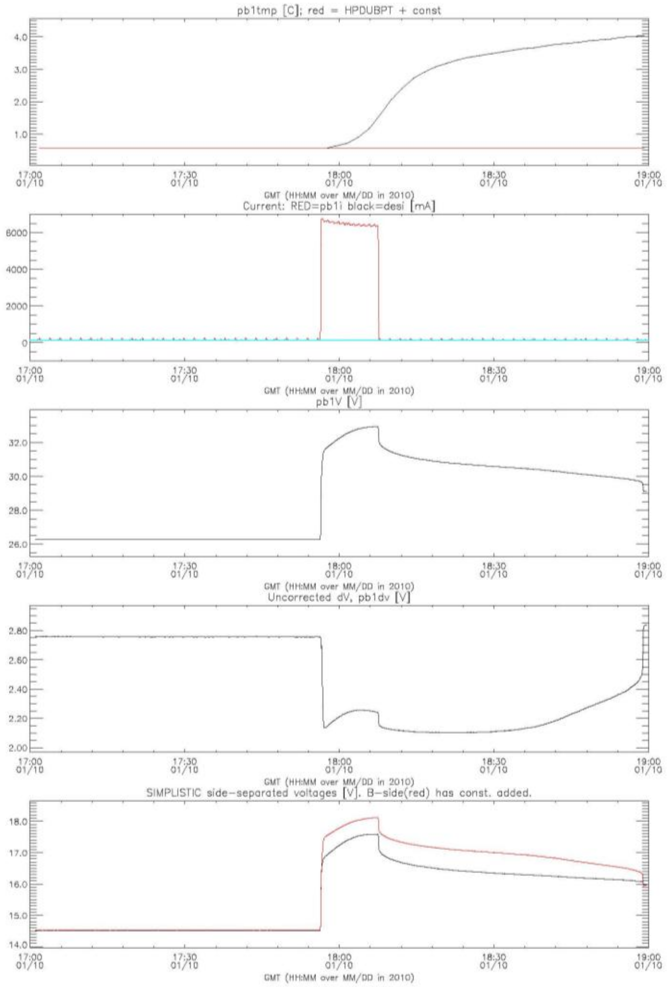


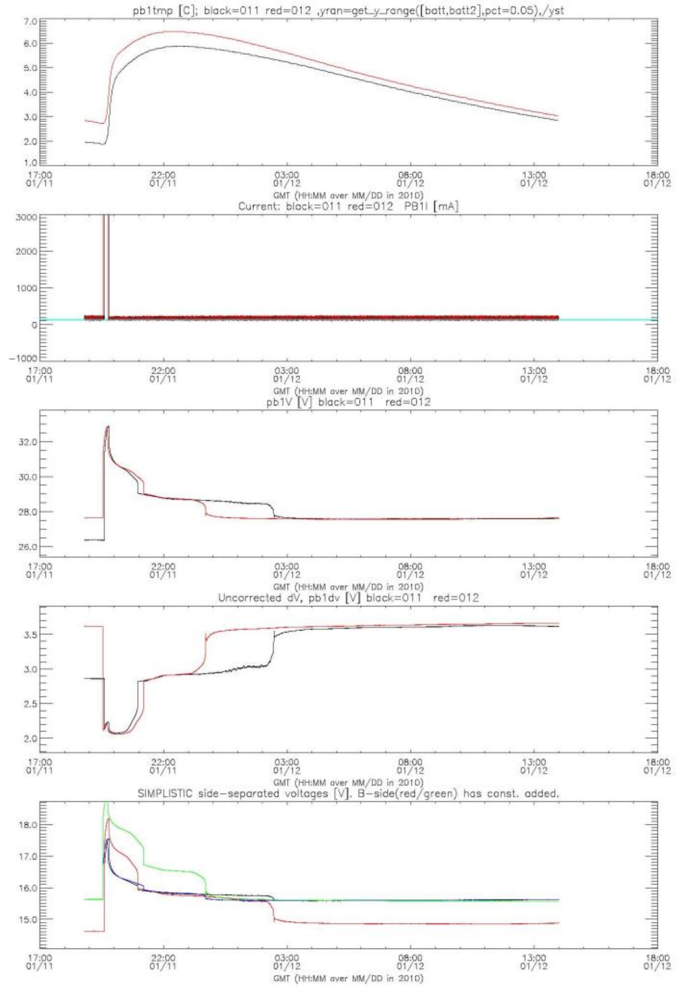
pb1tmp [C]; red = HPDUBPT + const
−0.50
−0.60
−0.70
−0.80
−0.90
13:00 01/07
13:12 01/07
13:24 01/07
13:36 01/07
13:48 01/07
14:00 01/07
GMT (HH:MM over MM/DD in 2010)
Current: RED=pb1i black=desi [mA]
3000
2000
1000
0
−1000
13:00 01/07
13:12 01/07
13:24 01/07
13:36 01/07
13:48 01/07
14:00 01/07
GMT (HH:MM over MM/DD in 2010)
pb1V [V]
32.0
30.0
28.0
26.0
24.0
13:00 01/07
13:12 01/07
13:24 01/07
13:36 01/07
13:48 01/07
14:00 01/07
GMT (HH:MM over MM/DD in 2010)
Uncorrected dV, pb1dv [V]
3.5
3.0
2.5
2.0
13:00 01/07
13:12 01/07
13:24 01/07
13:36 01/07
13:48 01/07
14:00 01/07
GMT (HH:MM over MM/DD in 2010)
SIMPLISTIC side−separated voltages [V]. B−side(red) has const. added.
18.0
17.0
16.0
15.0
14.0
13.0
13:00 01/07
13:12 01/07
13:24 01/07
13:36 01/07
13:48 01/07
14:00 01/07
GMT (HH:MM over MM/DD in 2010)


pb1tmp [C]; red = HPDUBPT + const
3.0
2.0
1.0
0.0
−1.0
−2.0
12:00 01/08
17:00 01/08
22:00 01/08
03:00 01/09
08:00 01/09
13:00 01/09
GMT (HH:MM over MM/DD in 2010)
Current: RED=pb1i black=desi [mA]
3000
2000
1000
0
−1000
pb1V [V]
34
32
30
28
26
24
Uncorrected dV, pb1dv [V]
3.5
3.0
2.5
2.0
SIMPLISTIC side−separated voltages [V]. B−side(red) has const. added.
19.0
18.0
17.0
16.0
15.0
14.0

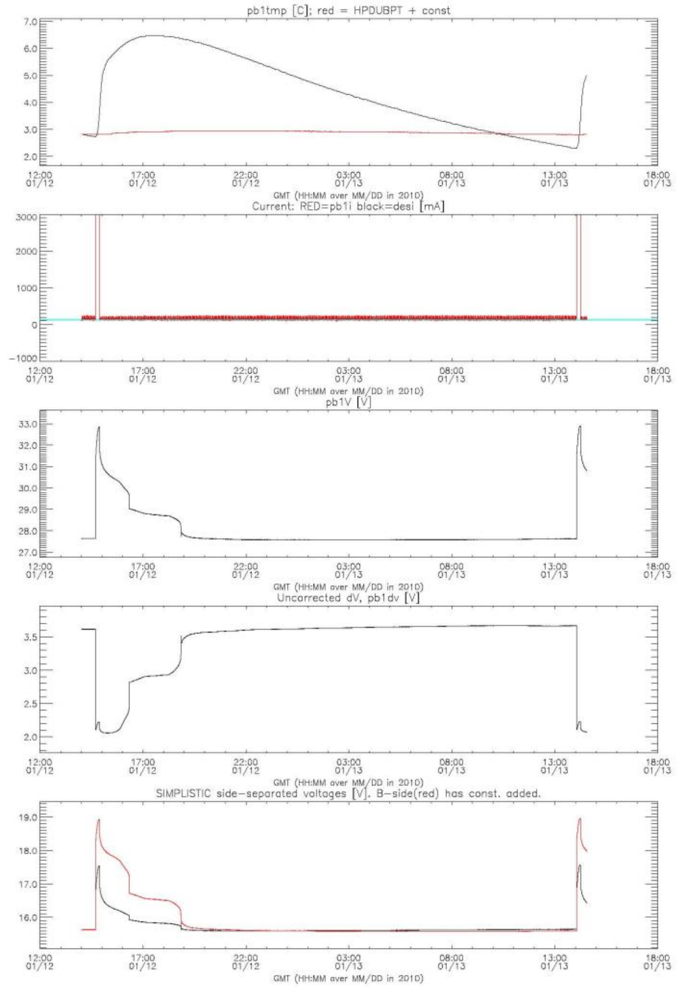


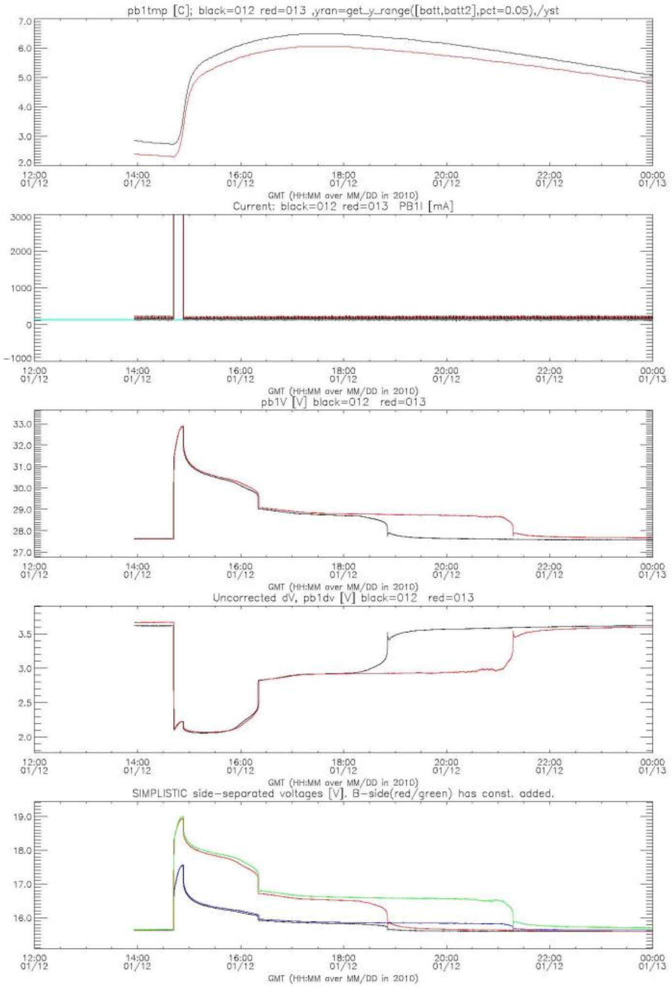
battery temps [C]: blck=PB1TMP red=PV4, grn= PV9, blu=BP
6.0
4.0
2.0
0.0
-2.0
17:00 01/10
22:00 01/10
03:00 01/11
08:00 01/11
13:00 01/11
18:00 01/11
GMT (HH:MM over MM/DD in 2010)
Current: RED=pb1i black=desi [mA]
10000
8000
6000
4000
2000
0
GMT (HH:MM over MM/DD in 2010)
pb1V [V]
32.0
30.0
28.0
26.0
GMT (HH:MM over MM/DD in 2010)
Uncorrected dV, pb1dv [V]
3.5
3.0
2.5
2.0
GMT (HH:MM over MM/DD in 2010)
SIMPLISTIC side-separated voltages [V], B-side(red) has const. added.
18.0
17.0
16.0
15.0
14.0
GMT (HH:MM over MM/DD in 2010)

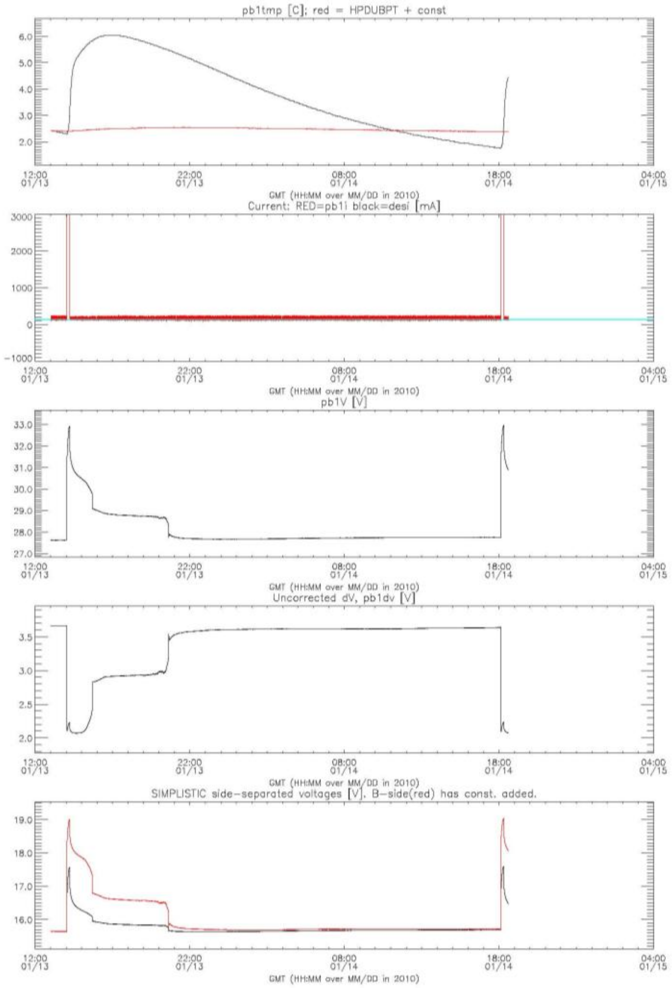

pb1tmp [C]; red = HPDUBPT + const
4.0
3.0
2.0
1.0
17:00 01/10
17:30 01/10
18:00 01/10
18:30 01/10
19:00 01/10
GMT (HH:MM over MM/DD in 2010)
Current: RED=pb1i black=desi [mA]
6000
4000
2000
0
17:00 01/10
17:30 01/10
18:00 01/10
18:30 01/10
19:00 01/10
GMT (HH:MM over MM/DD in 2010)
pb1V [V]
32.0
30.0
28.0
26.0
17:00 01/10
17:30 01/10
18:00 01/10
18:30 01/10
19:00 01/10
GMT (HH:MM over MM/DD in 2010)
Uncorrected dV, pb1dv [V]
2.80
2.60
2.40
2.20
2.00
17:00 01/10
17:30 01/10
18:00 01/10
18:30 01/10
19:00 01/10
GMT (HH:MM over MM/DD in 2010)
SIMPLISTIC side-separated voltages [V]. B-side(red) has const. added.
18.0
17.0
16.0
15.0
14.0
17:00 01/10
17:30 01/10
18:00 01/10
18:30 01/10
19:00 01/10
GMT (HH:MM over MM/DD in 2010)

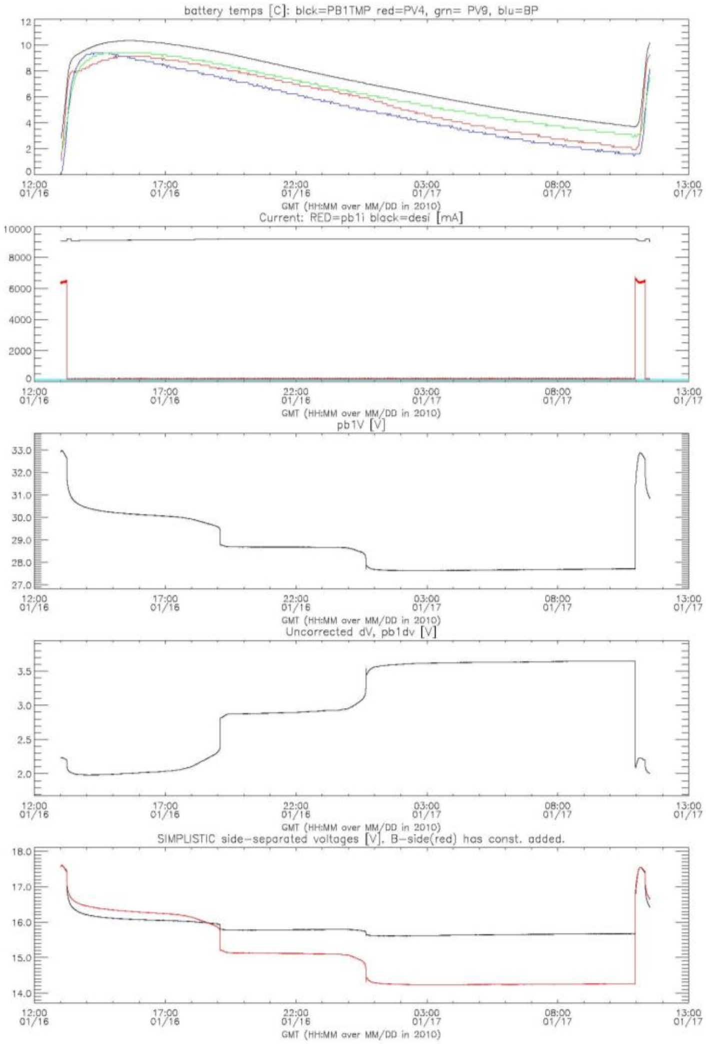


pb1tmp [C]; black=011 red=012 ,yran=get_y_range([batt,batt2],pct=0.05),/yst
7.0
6.0
5.0
4.0
3.0
2.0
1.0
17:00 01/11
22:00 01/11
03:00 01/12
08:00 01/12
13:00 01/12
18:00 01/12
GMT (HH:MM over MM/DD in 2010)
Current: black=011 red=012 PB1I [mA]
3000
2000
1000
0
−1000
17:00 01/11
22:00 01/11
03:00 01/12
08:00 01/12
13:00 01/12
18:00 01/12
GMT (HH:MM over MM/DD in 2010)
pb1V [V] black=011 red=012
32.0
30.0
28.0
26.0
17:00 01/11
22:00 01/11
03:00 01/12
08:00 01/12
13:00 01/12
18:00 01/12
GMT (HH:MM over MM/DD in 2010)
Uncorrected dV, pb1dv [V] black=011 red=012
3.5
3.0
2.5
2.0
17:00 01/11
22:00 01/11
03:00 01/12
08:00 01/12
13:00 01/12
18:00 01/12
GMT (HH:MM over MM/DD in 2010)
SIMPLISTIC side−separated voltages [V]. B−side(red/green) has const. added.
18.0
17.0
16.0
15.0
17:00 01/11
22:00 01/11
03:00 01/12
08:00 01/12
13:00 01/12
18:00 01/12
GMT (HH:MM over MM/DD in 2010)

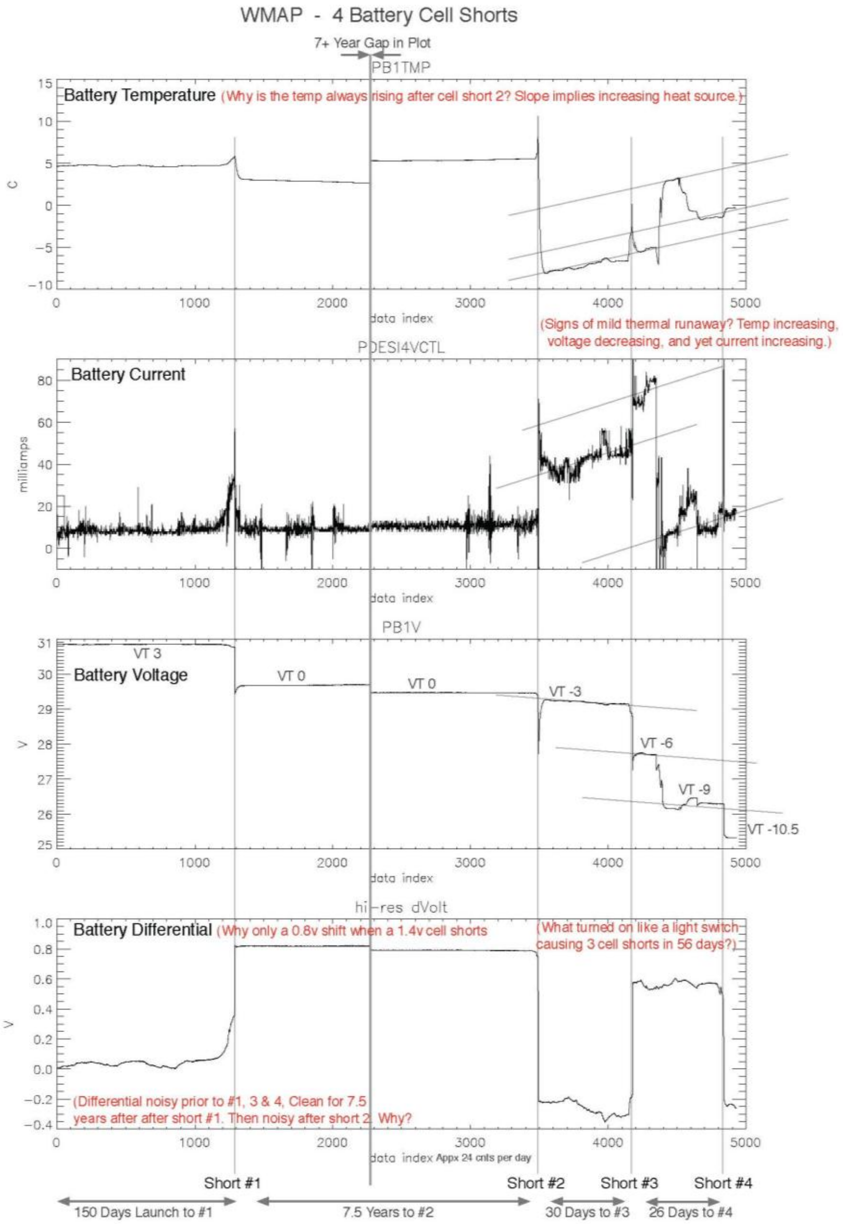

pb1tmp [C]; red = HPDUBPT + const
7.0
6.0
5.0
4.0
3.0
2.0
12:00 01/12
17:00 01/12
22:00 01/12
03:00 01/13
08:00 01/13
13:00 01/13
18:00 01/13
GMT (HH:MM over MM/DD in 2010)
Current: RED=pb1i black=desi [mA]
3000
2000
1000
0
−1000
pb1V [V]
33.0
32.0
31.0
30.0
29.0
28.0
27.0
Uncorrected dV, pb1dv [V]
3.5
3.0
2.5
2.0
SIMPLISTIC side−separated voltages [V]. B−side(red) has const. added.
19.0
18.0
17.0
16.0

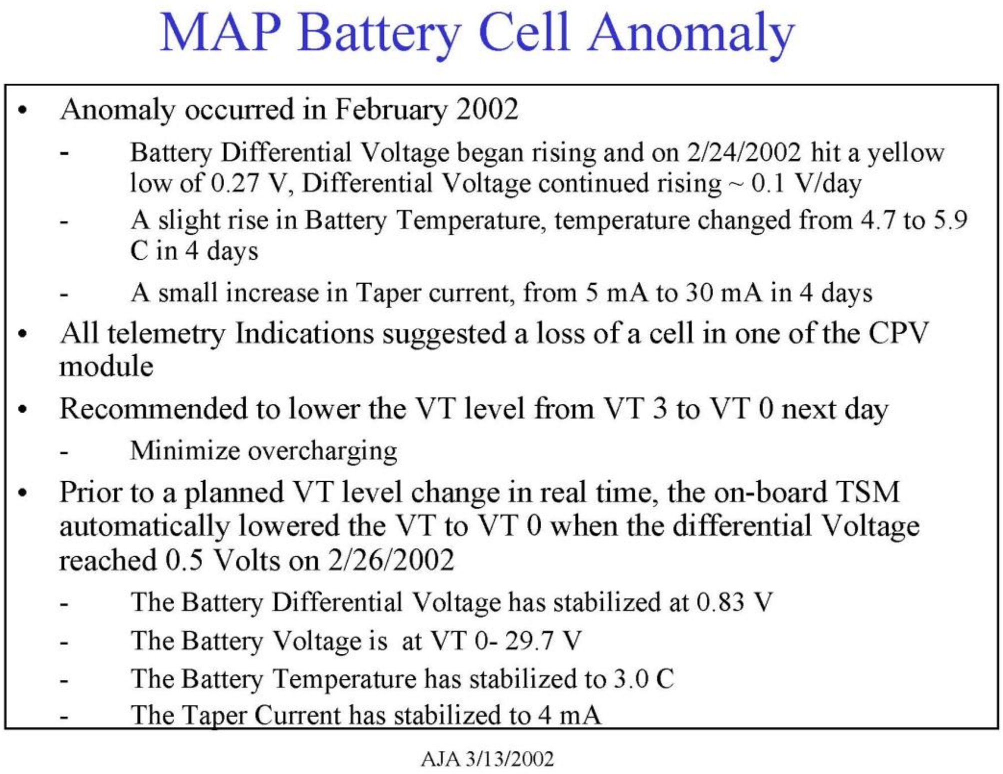

pb1tmp [C]; black=012 red=013 ,yran=get_y_range([batt,batt2],pct=0.05),/yst
7.0
6.0
5.0
4.0
3.0
2.0
12:00 01/12
14:00 01/12
16:00 01/12
18:00 01/12
20:00 01/12
22:00 01/12
00:00 01/13
GMT (HH:MM over MM/DD in 2010)
Current: black=012 red=013 PB1I [mA]
3000
2000
1000
0
−1000
pb1V [V] black=012 red=013
33.0
32.0
31.0
30.0
29.0
28.0
27.0
Uncorrected dV, pb1dv [V] black=012 red=013
3.5
3.0
2.5
2.0
SIMPLISTIC side−separated voltages [V]. B-side(red/green) has const. added.
19.0
18.0
17.0
16.0


pb1tmp [C]; red = HPDUBPT + const
6.0
5.0
4.0
3.0
2.0
12:00 01/13
22:00 01/13
08:00 01/14
18:00 01/14
04:00 01/15
GMT (HH:MM over MM/DD in 2010)
Current: RED=pb1i black=desi [mA]
3000
2000
1000
0
−1000
pb1V [V]
33.0
32.0
31.0
30.0
29.0
28.0
27.0
Uncorrected dV, pb1dv [V]
3.5
3.0
2.5
2.0
SIMPLISTIC side−separated voltages [V]. B−side(red) has const. added.
19.0
18.0
17.0
16.0


battery temps [C]: blck=PB1TMP red=PV4, grn= PV9, blu=BP
12
10
8
6
4
2
0
12:00 01/16
17:00 01/16
22:00 01/16
03:00 01/17
08:00 01/17
13:00 01/17
GMT (HH:MM over MM/DD in 2010)
Current: RED=pb1i black=desi [mA]
10000
8000
6000
4000
2000
0
GMT (HH:MM over MM/DD in 2010)
pb1V [V]
33.0
32.0
31.0
30.0
29.0
28.0
27.0
GMT (HH:MM over MM/DD in 2010)
Uncorrected dV, pb1dv [V]
3.5
3.0
2.5
2.0
GMT (HH:MM over MM/DD in 2010)
SIMPLISTIC side-separated voltages [V], B-side(red) has const. added.
18.0
17.0
16.0
15.0
14.0
GMT (HH:MM over MM/DD in 2010)

WMAP - Battery Cell Shorts





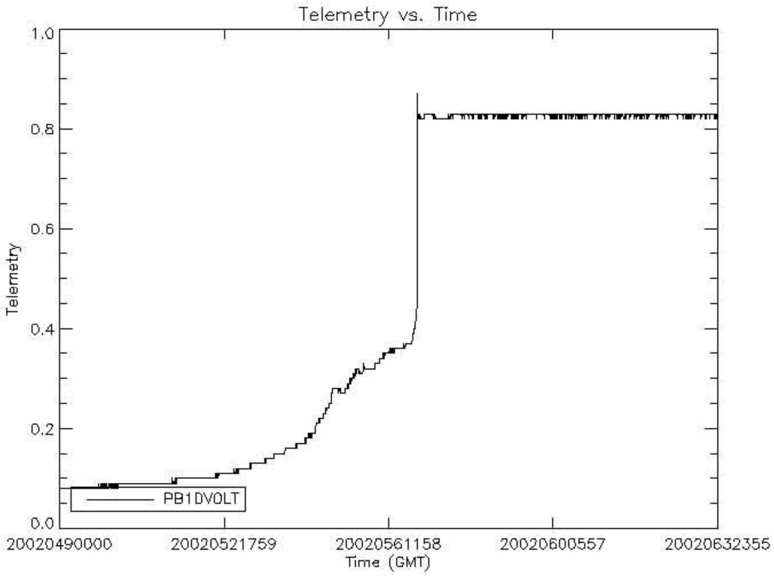
MAP Battery Cell Anomaly

- Anomaly occurred in February 2002
  - Battery Differential Voltage began rising and on 2/24/2002 hit a yellow low of 0.27 V, Differential Voltage continued rising ~ 0.1 V/day
  - A slight rise in Battery Temperature, temperature changed from 4.7 to 5.9 C in 4 days
  - A small increase in Taper current, from 5 mA to 30 mA in 4 days
- All telemetry Indications suggested a loss of a cell in one of the CPV module
- Recommended to lower the VT level from VT 3 to VT 0 next day
  - Minimize overcharging
- Prior to a planned VT level change in real time, the on-board TSM automatically lowered the VT to VT 0 when the differential Voltage reached 0.5 Volts on 2/26/2002
  - The Battery Differential Voltage has stabilized at 0.83 V
  - The Battery Voltage is at VT 0- 29.7 V
  - The Battery Temperature has stabilized to 3.0 C
  - The Taper Current has stabilized to 4 mA

AJA 3/13/2002

MAP Battery Cell Anomaly 2/24/2002

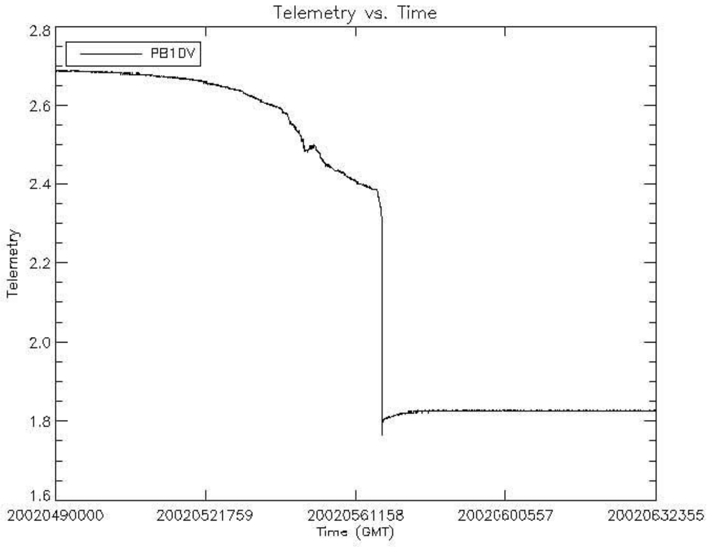
Battery Differential Voltage Plot



AJA 3/13/2002

MAP Battery Cell Anomaly 2/24/2002

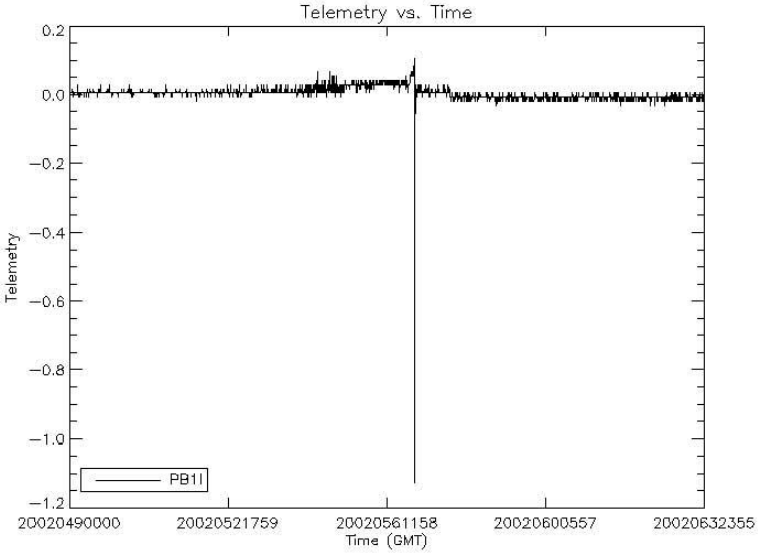
Battery Differential Voltage Plot (1 CPV)



AJA 3/13/2002

MAP Battery Cell Anomaly 2/24/2002

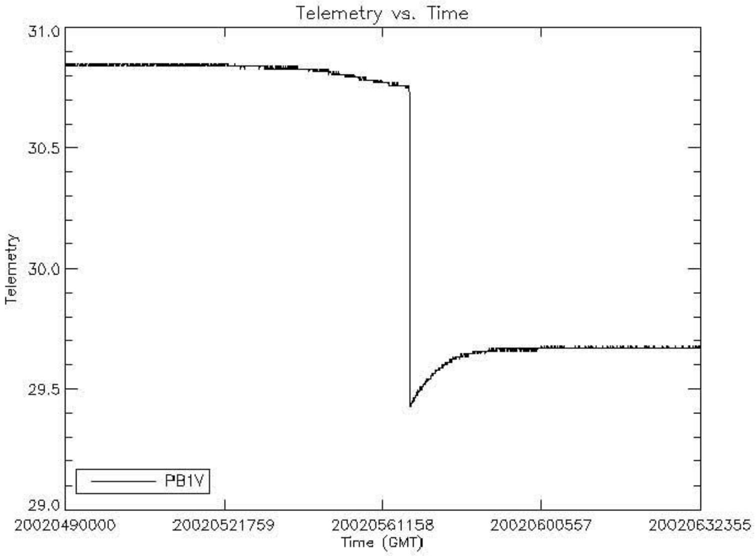
Battery Current Plot



AJA 3/13/2002

MAP Battery Cell Anomaly 2/24/2002

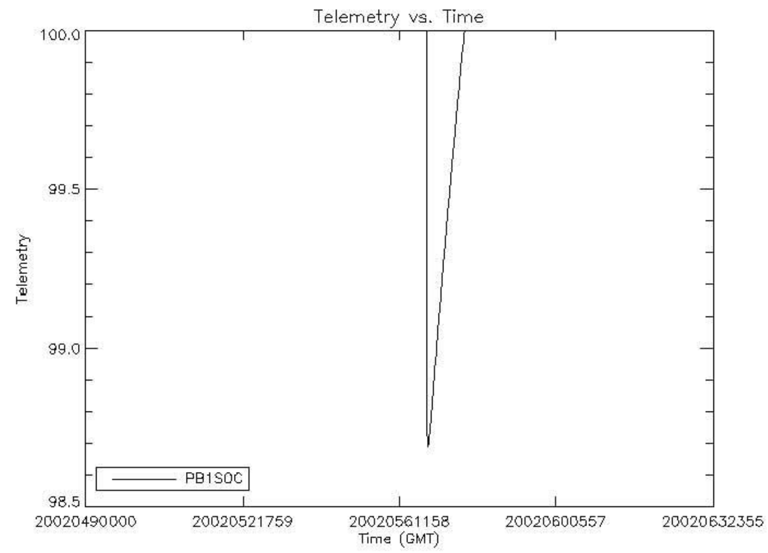
Battery Voltage Plot



AJA 3/13/2002

MAP Battery Cell Anomaly 2/24/2002

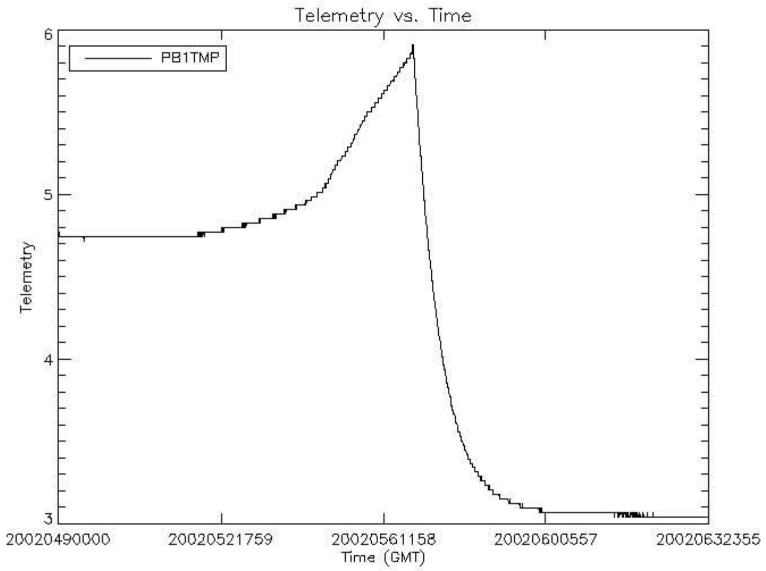
Battery State of Charge Plot



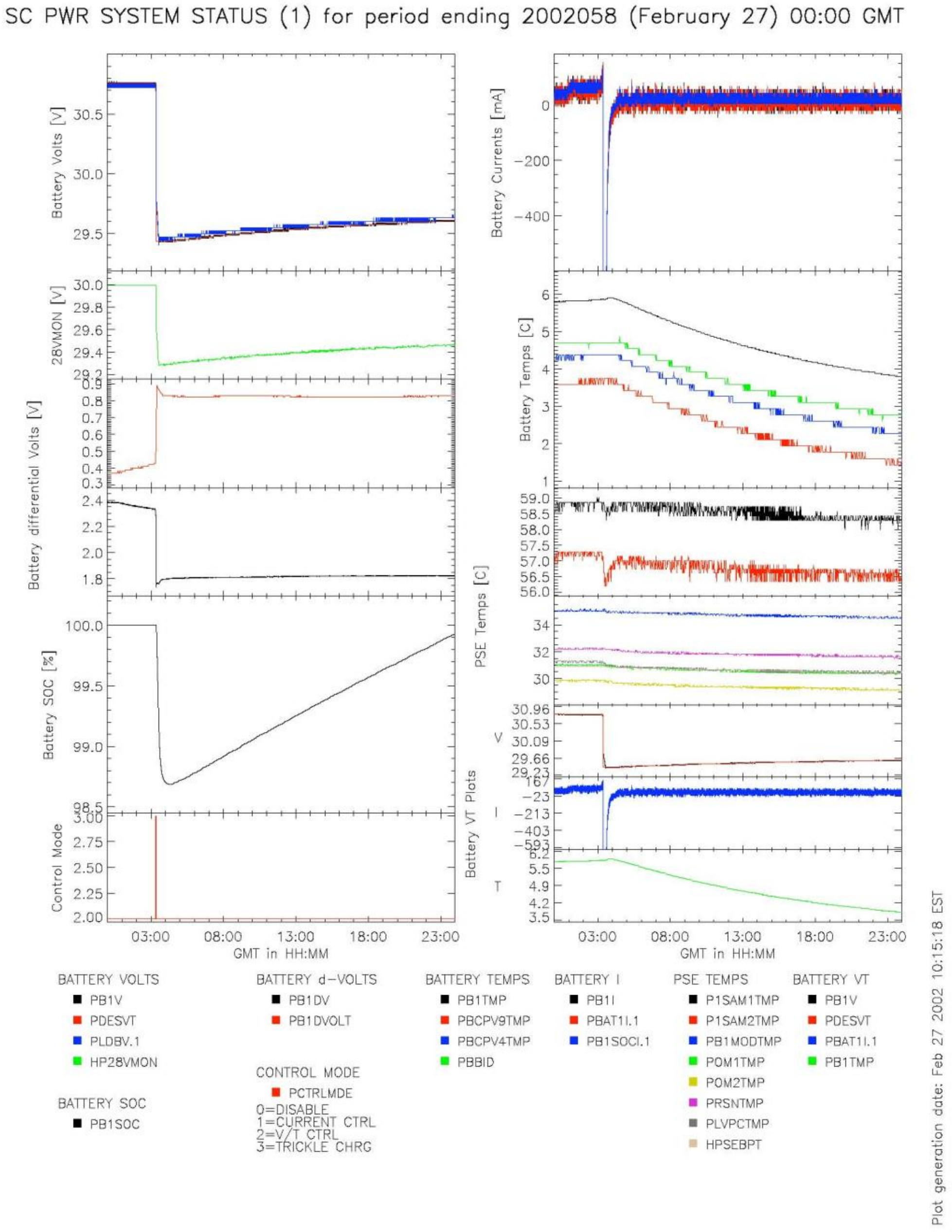
AJA 3/13/2002

MAP Battery Cell Anomaly 2/24/2002

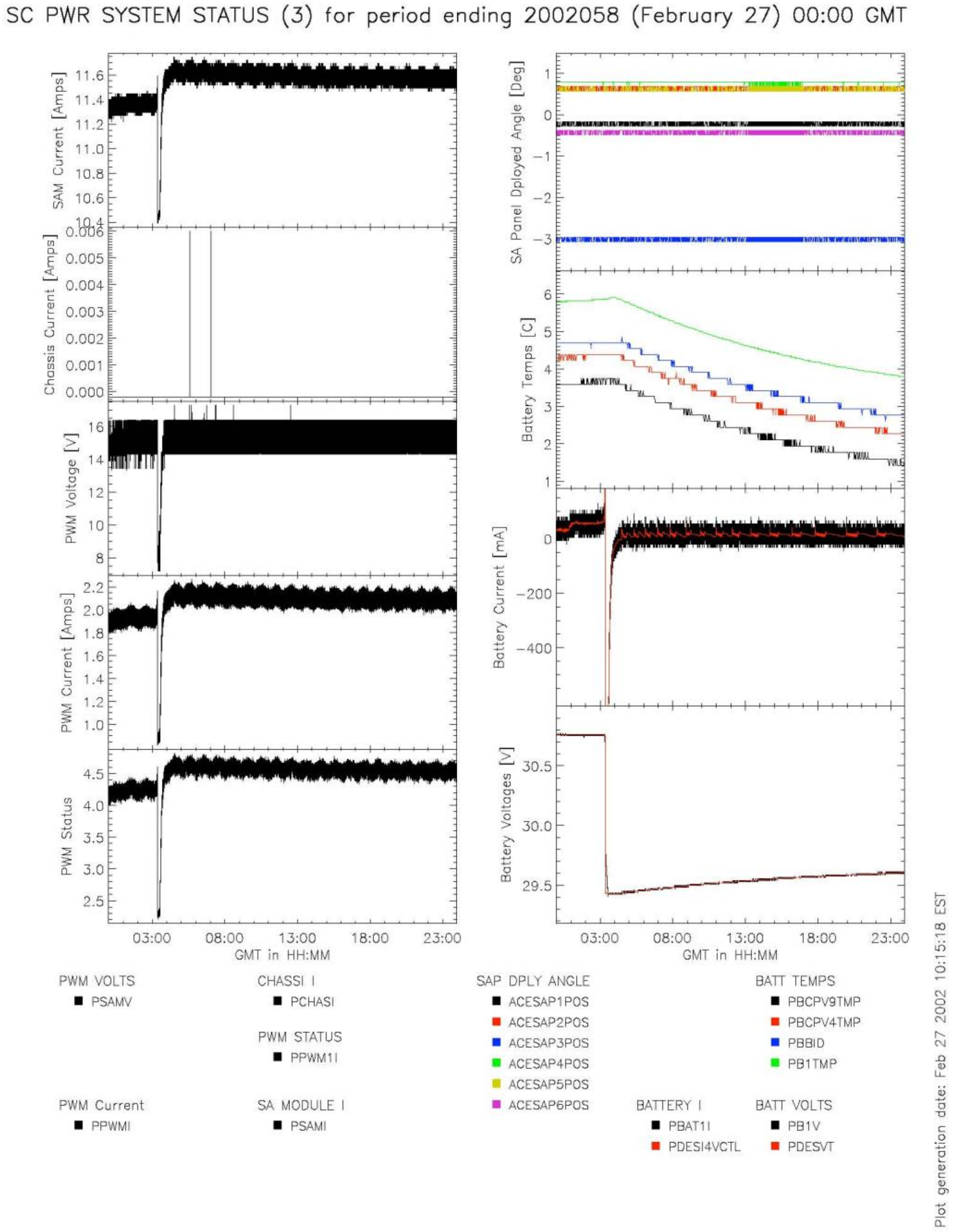
Battery Temperature Plot

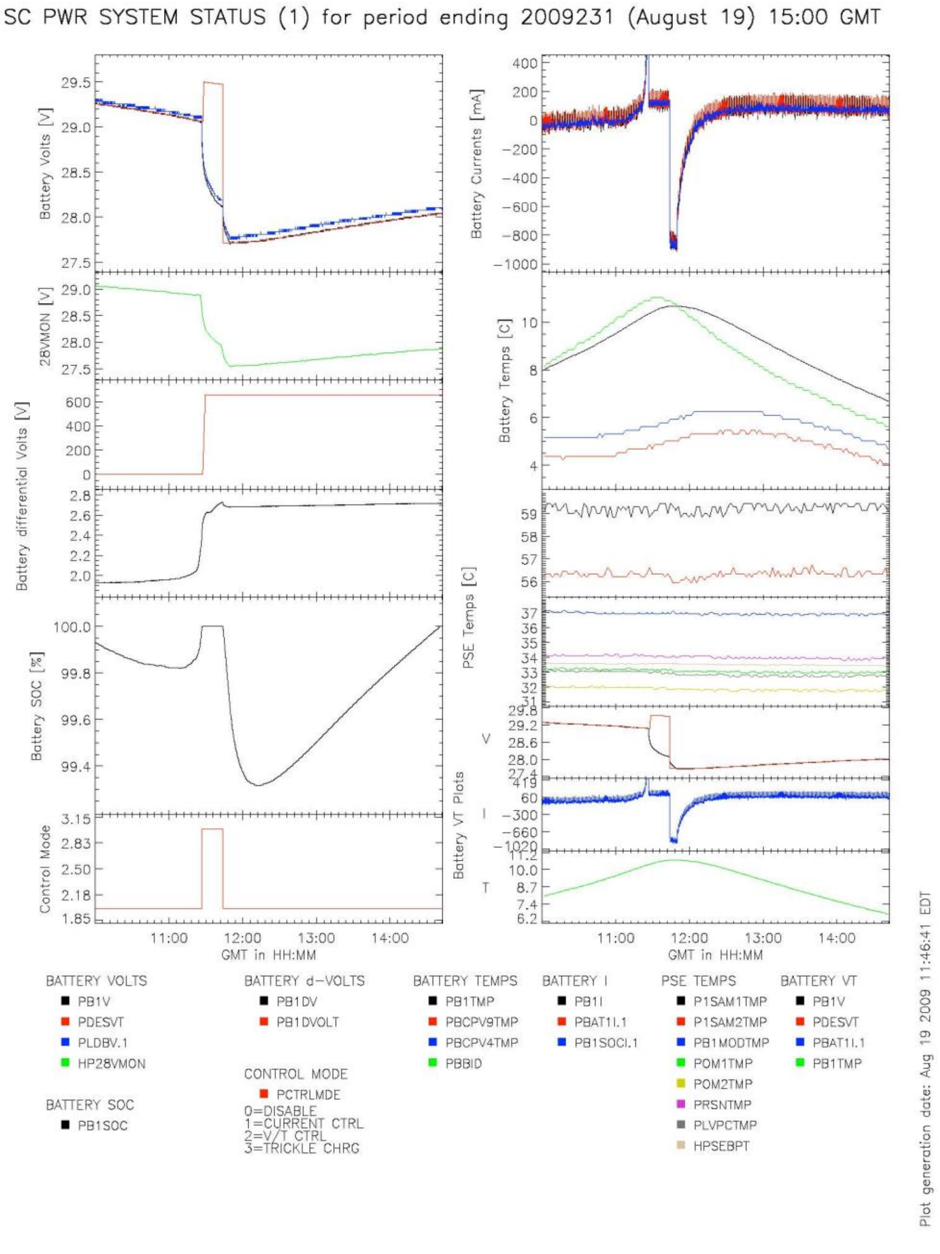


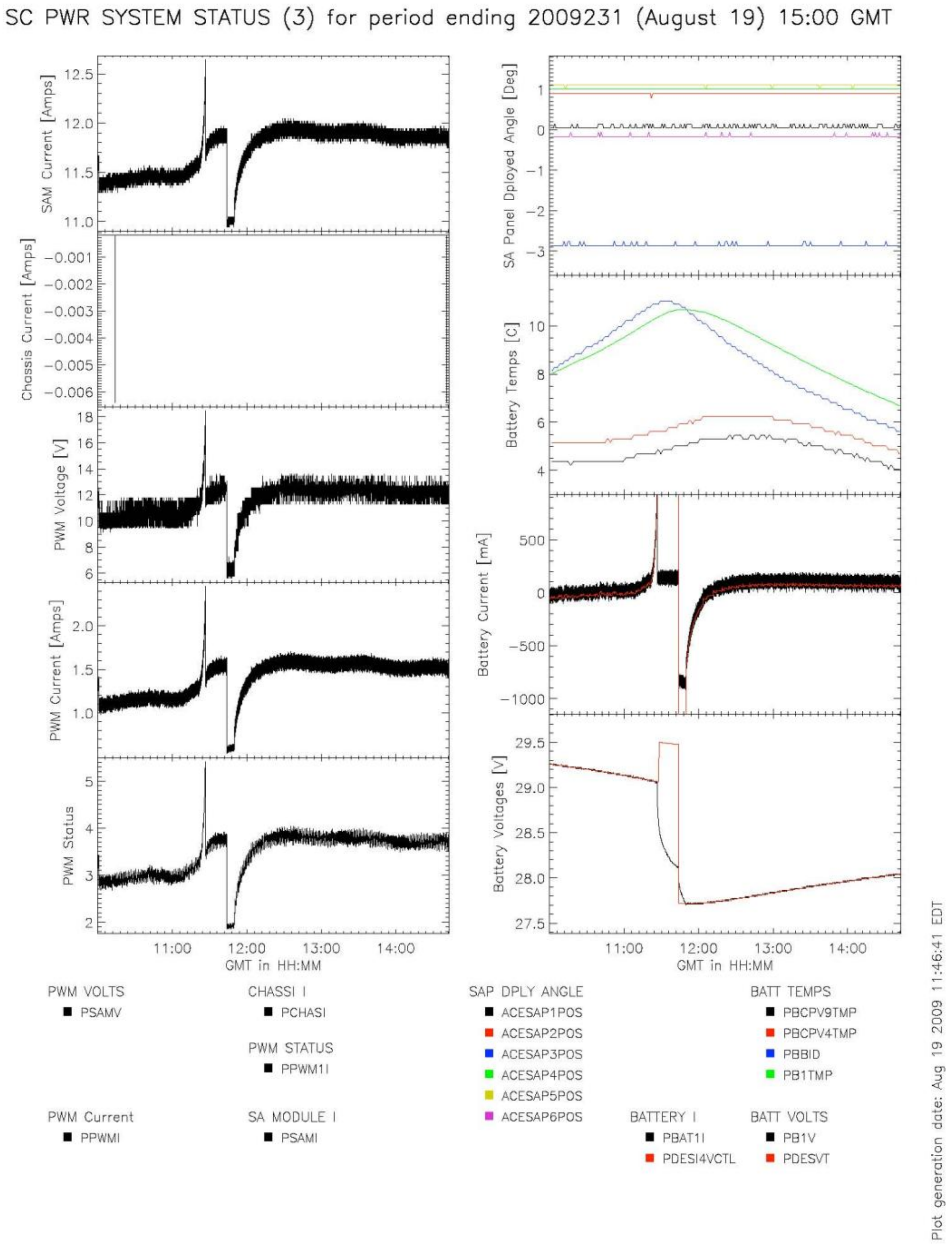
AJA 3/13/2002

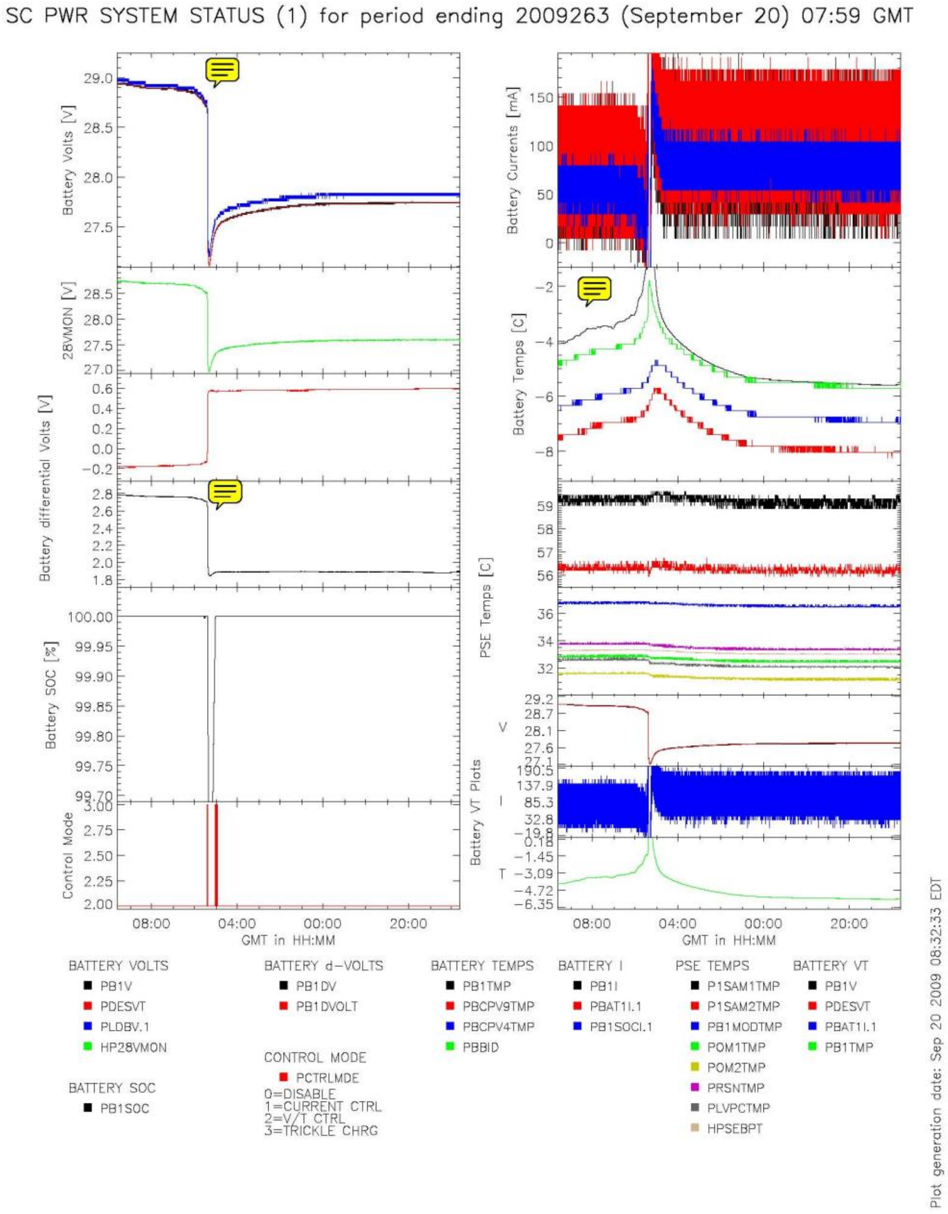


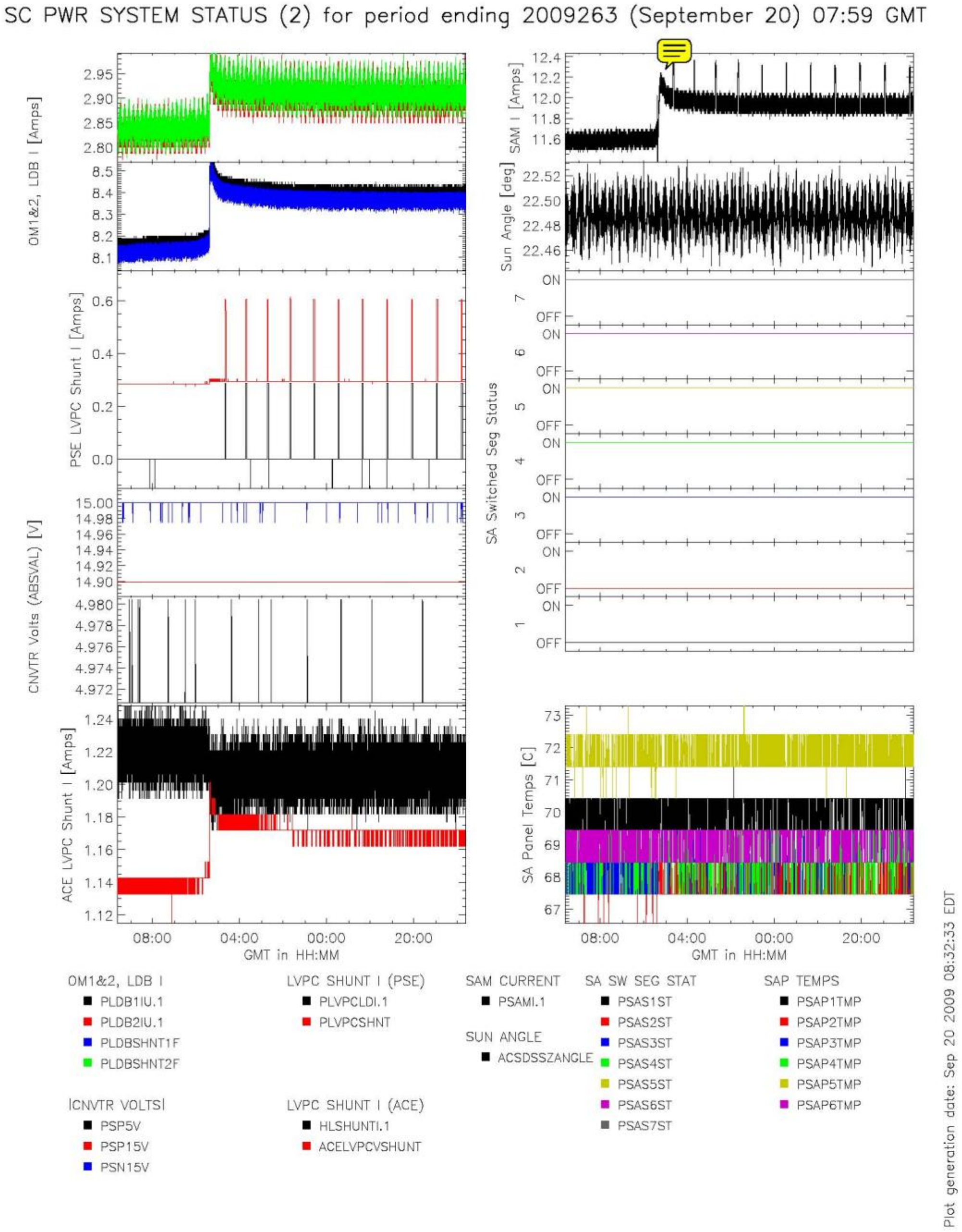
SC PWR SYSTEM STATUS (1) for period ending 2002058 (February 27) 00:00 GMT
Battery Volts [V]
30.5
30.0
29.5
28VMON [V]
30.0
29.8
29.6
29.4
29.2
Battery differential Volts [V]
0.9
0.8
0.7
0.6
0.5
0.4
0.3
2.4
2.2
2.0
1.8
Battery SOC [%]
100.0
99.5
99.0
98.5
Control Mode
3.00
2.75
2.50
2.25
2.00
03:00
08:00
13:00
18:00
23:00
GMT in HH:MM
Battery Currents [mA]
0
−200
−400
Battery Temps [C]
6
5
4
3
2
1
PSE Temps [C]
59.0
58.5
58.0
57.5
57.0
56.5
56.0
34
32
30
Battery VT Plots
V
30.96
30.53
30.09
29.66
29.23
I
167
−23
−213
−403
−593
T
6.2
5.5
4.9
4.2
3.5
03:00
08:00
13:00
18:00
23:00
GMT in HH:MM
BATTERY VOLTS
■ PB1V
■ PDESVT
■ PLDBV.1
■ HP28VMON
BATTERY SOC
■ PB1SOC
BATTERY d-VOLTS
■ PB1DV
■ PB1DVOLT
CONTROL MODE
■ PCTRLMDE
0=DISABLE
1=CURRENT CTRL
2=V/T CTRL
3=TRICKLE CHRG
BATTERY TEMPS
■ PB1TMP
■ PBCPV9TMP
■ PBCPV4TMP
■ PBBID
BATTERY I
■ PB1I
■ PBAT1I.1
■ PB1SOCI.1
PSE TEMPS
■ P1SAM1TMP
■ P1SAM2TMP
■ PB1MODTMP
■ POM1TMP
■ POM2TMP
■ PRSNTMP
■ PLVPCTMP
■ HPSEBPT
BATTERY VT
■ PB1V
■ PDESVT
■ PBAT1I.1
■ PB1TMP
Plot generation date: Feb 27 2002 10:15:18 EST


SC PWR SYSTEM STATUS (3) for period ending 2002058 (February 27) 00:00 GMT
SAM Current [Amps]
11.6
11.4
11.2
11.0
10.8
10.6
10.4
Chassis Current [Amps]
0.006
0.005
0.004
0.003
0.002
0.001
0.000
PWM Voltage [V]
16
14
12
10
8
PWM Current [Amps]
2.2
2.0
1.8
1.6
1.4
1.2
1.0
PWM Status
4.5
4.0
3.5
3.0
2.5
03:00
08:00
13:00
18:00
23:00
GMT in HH:MM
SA Panel Dployed Angle [Deg]
1
0
−1
−2
−3
Battery Temps [C]
6
5
4
3
2
1
Battery Current [mA]
0
−200
−400
Battery Voltages [V]
30.5
30.0
29.5
03:00
08:00
13:00
18:00
23:00
GMT in HH:MM
PWM VOLTS
PSAMV
CHASSI I
PCHASI
PWM STATUS
PPWM1I
PWM Current
PPWMI
SA MODULE I
PSAMI
SAP DPLY ANGLE
ACESAP1POS
ACESAP2POS
ACESAP3POS
ACESAP4POS
ACESAP5POS
ACESAP6POS
BATT TEMPS
PBCPV9TMP
PBCPV4TMP
PBBID
PB1TMP
BATTERY I
PBAT1I
PDESI4VCTL
BATT VOLTS
PB1V
PDESVT
Plot generation date: Feb 27 2002 10:15:18 EST


SC PWR SYSTEM STATUS (1) for period ending 2009231 (August 19) 15:00 GMT


SC PWR SYSTEM STATUS (3) for period ending 2009231 (August 19) 15:00 GMT
SAM Current [Amps]
Chassis Current [Amps]
PWM Voltage [V]
PWM Current [Amps]
PWM Status
SA Panel Dployed Angle [Deg]
Battery Temps [C]
Battery Current [mA]
Battery Voltages [V]
11:00
12:00
13:00
14:00
GMT in HH:MM
PWM VOLTS
■ PSAMV
CHASSI I
■ PCHASI
PWM STATUS
■ PPWM1I
PWM Current
■ PPWMI
SA MODULE I
■ PSAMI
SAP DPLY ANGLE
■ ACESAP1POS
■ ACESAP2POS
■ ACESAP3POS
■ ACESAP4POS
■ ACESAP5POS
■ ACESAP6POS
BATT TEMPS
■ PBCPV9TMP
■ PBCPV4TMP
■ PBBID
■ PB1TMP
BATTERY I
■ PBAT1I
■ PDESI4VCTL
BATT VOLTS
■ PB1V
■ PDESVT
Plot generation date: Aug 19 2009 11:46:41 EDT


SC PWR SYSTEM STATUS (1) for period ending 2009263 (September 20) 07:59 GMT
Battery Volts [V]
29.0
28.5
28.0
27.5
28VMON [V]
28.5
28.0
27.5
27.0
Battery differential Volts [V]
0.6
0.4
0.2
0.0
−0.2
2.8
2.6
2.4
2.2
2.0
1.8
Battery SOC [%]
100.00
99.95
99.90
99.85
99.80
99.75
99.70
Control Mode
3.00
2.75
2.50
2.25
2.00
08:00
04:00
00:00
20:00
GMT in HH:MM
Battery Currents [mA]
150
100
50
0
Battery Temps [C]
−2
−4
−6
−8
PSE Temps [C]
59
58
57
56
36
34
32
Battery VT Plots
V
29.2
28.7
28.1
27.6
27.1
I
190.5
137.9
85.3
32.8
−19.8
T
0.18
−1.45
−3.09
−4.72
−6.35
08:00
04:00
00:00
20:00
GMT in HH:MM
BATTERY VOLTS
■ PB1V
■ PDESVT
■ PLDBV.1
■ HP28VMON
BATTERY SOC
■ PB1SOC
BATTERY d−VOLTS
■ PB1DV
■ PB1DVOLT
CONTROL MODE
■ PCTRLMDE
0=DISABLE
1=CURRENT CTRL
2=V/T CTRL
3=TRICKLE CHRG
BATTERY TEMPS
■ PB1TMP
■ PBCPV9TMP
■ PBCPV4TMP
■ PBBID
BATTERY I
■ PB1I
■ PBAT1I.1
■ PB1SOCI.1
PSE TEMPS
■ P1SAM1TMP
■ P1SAM2TMP
■ PB1MODTMP
■ POM1TMP
■ POM2TMP
■ PRSNTMP
■ PLVPCTMP
■ HPSEBPT
BATTERY VT
■ PB1V
■ PDESVT
■ PBAT1I.1
■ PB1TMP
Plot generation date: Sep 20 2009 08:32:33 EDT


SC PWR SYSTEM STATUS (2) for period ending 2009263 (September 20) 07:59 GMT
OM1&2, LDB I [Amps]
2.95
2.90
2.85
2.80
8.5
8.4
8.3
8.2
8.1
PSE LVPC Shunt I [Amps]
0.6
0.4
0.2
0.0
CNVTR Volts (ABSVAL) [V]
15.00
14.98
14.96
14.94
14.92
14.90
4.980
4.978
4.976
4.974
4.972
ACE LVPC Shunt I [Amps]
1.24
1.22
1.20
1.18
1.16
1.14
1.12
08:00
04:00
00:00
20:00
GMT in HH:MM
SAM I [Amps]
12.4
12.2
12.0
11.8
11.6
Sun Angle [deg]
22.52
22.50
22.48
22.46
SA Switched Seg Status
7
6
5
4
3
2
1
ON
OFF
SA Panel Temps [C]
73
72
71
70
69
68
67
08:00
04:00
00:00
20:00
GMT in HH:MM
OM1&2, LDB I
PLDB1IU.1
PLDB2IU.1
PLDBSHNT1F
PLDBSHNT2F
|CNVTR VOLTS|
PSP5V
PSP15V
PSN15V
LVPC SHUNT I (PSE)
PLVPCLDI.1
PLVPCSHNT
LVPC SHUNT I (ACE)
HLSHUNTI.1
ACELVPCVSHUNT
SAM CURRENT
PSAMI.1
SUN ANGLE
ACSDSSZANGLE
SA SW SEG STAT
PSAS1ST
PSAS2ST
PSAS3ST
PSAS4ST
PSAS5ST
PSAS6ST
PSAS7ST
SAP TEMPS
PSAP1TMP
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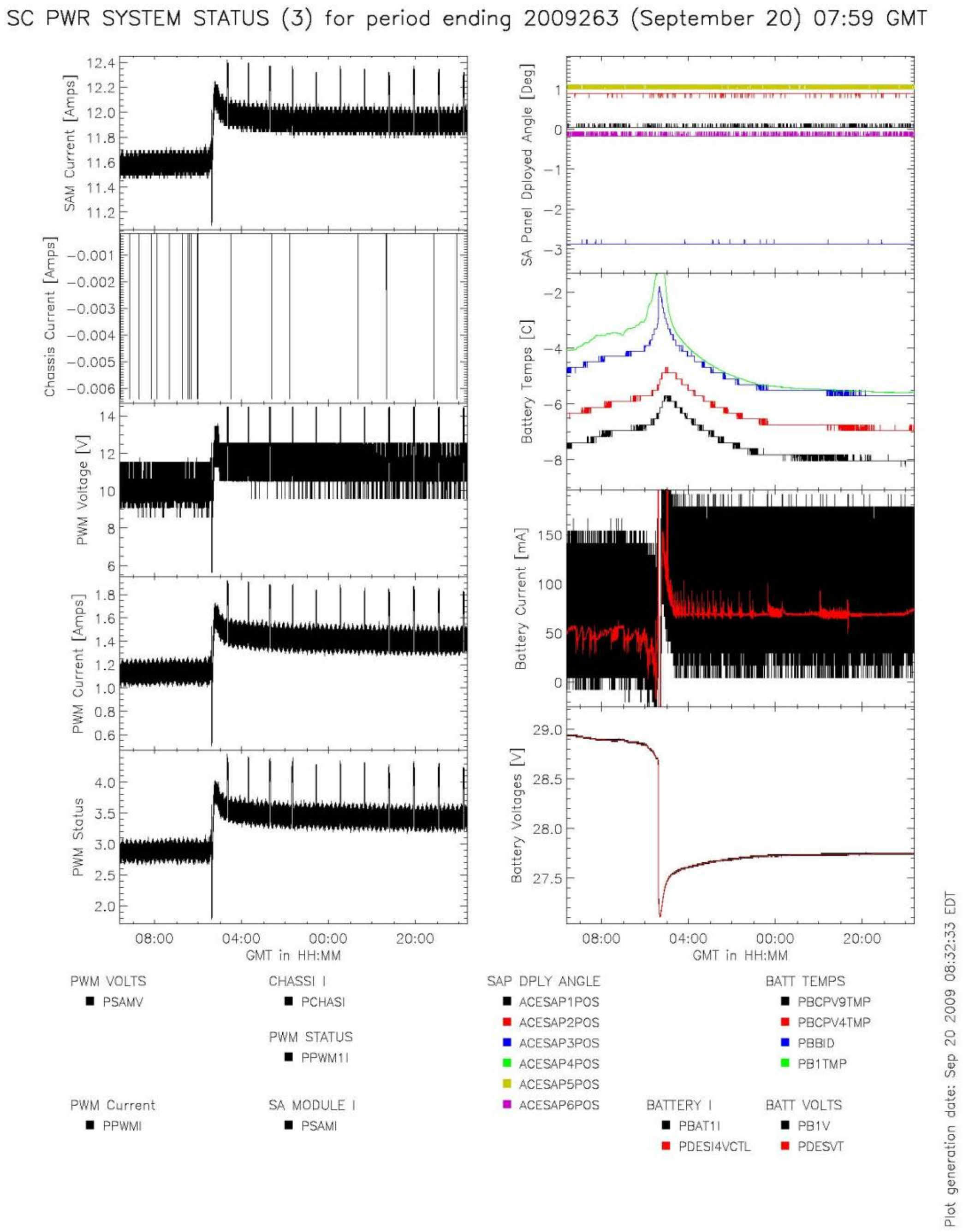
PSAP3TMP
PSAP4TMP
PSAP5TMP
PSAP6TMP
Plot generation date: Sep 20 2009 08:32:33 EDT


SC PWR SYSTEM STATUS (3) for period ending 2009263 (September 20) 07:59 GMT
SAM Current [Amps]
12.4
12.2
12.0
11.8
11.6
11.4
11.2
Chassis Current [Amps]
−0.001
−0.002
−0.003
−0.004
−0.005
−0.006
PWM Voltage [V]
14
12
10
8
6
PWM Current [Amps]
1.8
1.6
1.4
1.2
1.0
0.8
0.6
PWM Status
4.0
3.5
3.0
2.5
2.0
08:00
04:00
00:00
20:00
GMT in HH:MM
SA Panel Dployed Angle [Deg]
1
0
−1
−2
−3
Battery Temps [C]
−2
−4
−6
−8
Battery Current [mA]
150
100
50
0
Battery Voltages [V]
29.0
28.5
28.0
27.5
08:00
04:00
00:00
20:00
GMT in HH:MM
PWM VOLTS
■ PSAMV
CHASSI I
■ PCHASI
PWM STATUS
■ PPWM1I
PWM Current
■ PPWMI
SA MODULE I
■ PSAMI
SAP DPLY ANGLE
■ ACESAP1POS
■ ACESAP2POS
■ ACESAP3POS
■ ACESAP4POS
■ ACESAP5POS
■ ACESAP6POS
BATT TEMPS
■ PBCPV9TMP
■ PBCPV4TMP
■ PBBID
■ PB1TMP
BATTERY I
■ PBAT1I
■ PDESI4VCTL
BATT VOLTS
■ PB1V
■ PDESVT
Plot generation date: Sep 20 2009 08:32:33 EDT

Appendix B. Battery Test Plan for WMAP Investigation

TEST SEQUENCE FOR WMAP 23 Ah Battery (Flight Spare)

Reconditioning at 10°C.

Purpose: To "wake up" the battery
Charge Regimen: C/20 rate (1.15 A) for 48 or more hours
Discharge Regimen: C/2 rate (11.5 A) to 1.8 V per CPV (22V/battery)

MAP Handling Plan Parameters:
Charge Regimen: C/20 rate (1.15 A) for 40 hours
Discharge Regimen: C/2 rate (11.5 A) to 0.9 V per cell+1.8V per CPV (22 V/battery)

Note: After making discharge limit change...Only difference is charge time.

Standard Capacity Cycle at 10°C.

Purpose: To measure the standard capacity of the battery.
Charge Regimen: C/10 rate (2.3 A) for 16 hours
Discharge Regimen: C/2 rate (11.5 A) to 1.8 V per CPV (22V/battery)

Charge Retention at 10°C at full state of charge.

Purpose: To check for evidence of internal shorting.
Charge Regimen: C/10 rate (2.3 A) for 16 hours
After full charge, the cell is open circuited for 72 hours,
then discharge at C/2 rate (11.5 A) to 1.8 V per CPV (22V/battery)

Determine the self-discharge rate based on pressure curves.

Trickle Charge Testing at 10°C

Purpose: Determine if low trickle rate reduces active nickel.
Charge Regimen: C/10 rate (2.3 A) for 16 hours

After full charge, the battery is put into trickle charge at 10 mA (C/2300),
After 2 weeks confirm if 10 mA has been sufficient to keep battery above self-discharge rate.

If not: then discharge battery at C/2 to determine charge remaining

If yes: then discharge at C/2 rate to 90 % DOD.

Again, the battery is put into trickle charge at 10 mA,
After another 2 weeks confirm that 10 mA has been sufficient to keep battery above self-discharge rate.

Change charge conditions to V/T clamp at measured battery voltage
Continue test for additional 2 weeks

Increase trickle charge rate to C/200 for 1 week to determine battery response

After 1 week begin pulse charging to determine if cell recovery can be achieved similarly to on-orbit, monitor response to see if recovered cell re-collapses

TEST SEQUENCE FOR HST 90 Ah Cells (Parallel Test Program)

Reconditioning at 10°C.
Purpose: To "wake up" the cells
Charge Regimen: C/20 rate (4.5 A) for 48 or more hours
Discharge Regimen: C/2 rate (45 A) to 1.0 V per cell

Standard Capacity Cycle at 10°C.
Purpose: To measure the standard capacity of the battery.
Charge Regimen: C/10 rate (9 A) for 16 hours
Discharge Regimen: C/2 rate (45 A) to 1.0 V per cell

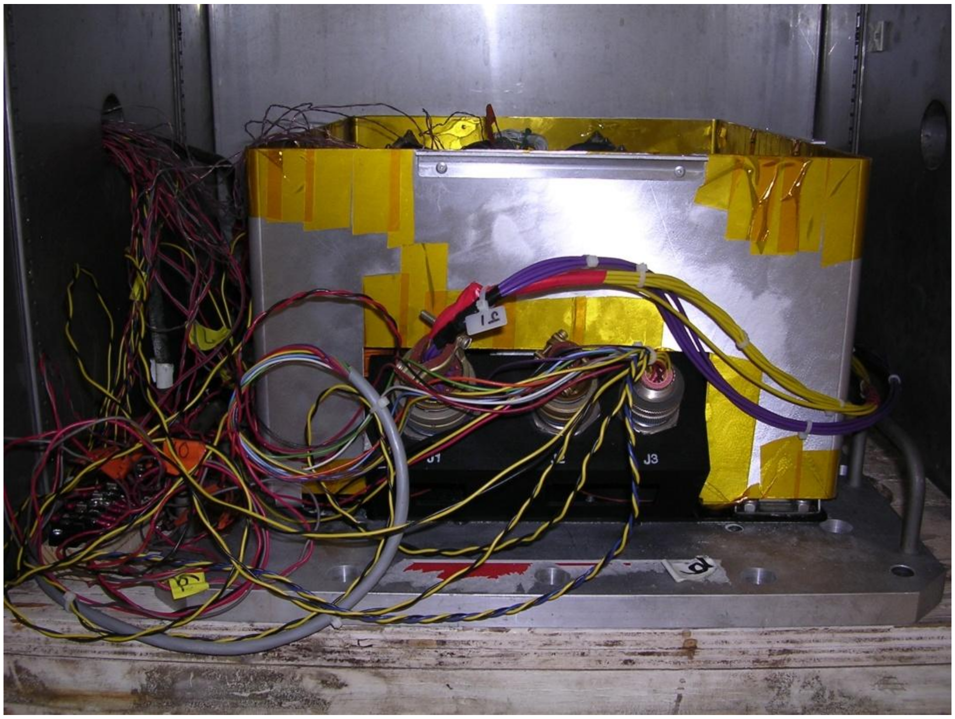
Charge Retention at 10°C at full state of charge.
Purpose: To check for evidence of internal shorting.
Charge Regimen: C/10 rate (9 A) for 16 hours
After full charge, the cell is open circuited for 72 hours,
then discharge at C/2 rate (45 A) to 1.0 V per cell

Determine the self-discharge rate based on pressure curves.

Trickle Charge Testing at 10°C
Purpose: Determine if low trickle rate reduces active nickel.
Charge Regimen: C/10 rate (9 A) for 16 hours
Same options as WMAP Flight Spare Battery Test Plan

Appendix C. Significant Flight Battery Test Results

The flight spare battery cells were instrumented with voltage and temperature sensors and configured inside a temperature chamber as shown in the figure below.



The battery capacity determined at 11.5A discharge rate at 5 o C was 31.1 Ah with CPV vessel controlling the capacity. The charge retention for the battery in the 72-hour test was 66% (to 2V).

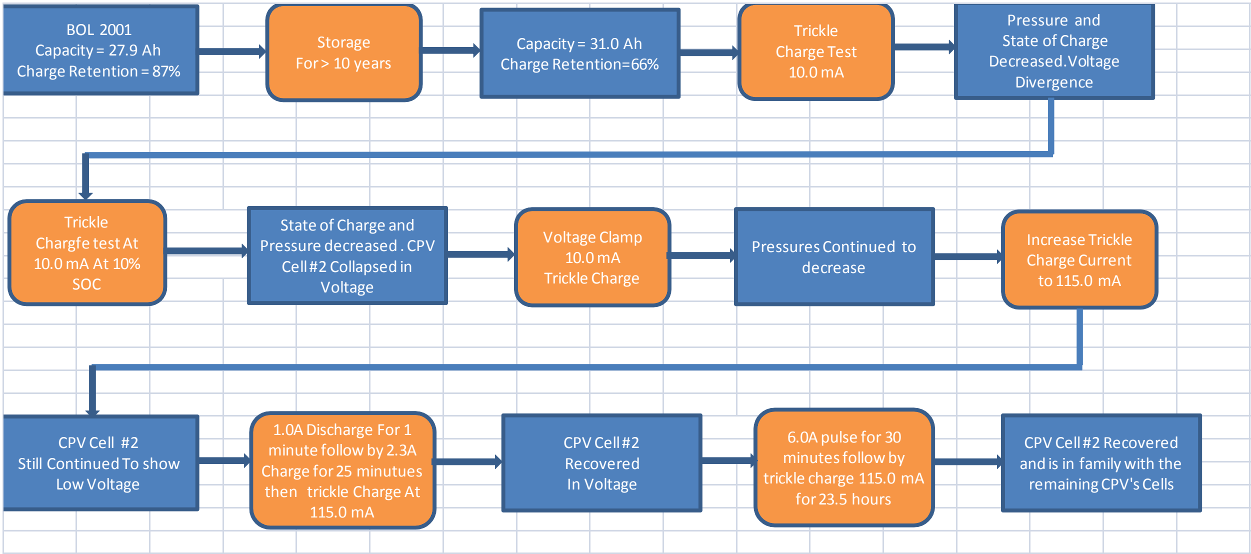
The battery capacity determined at 11.5A discharge rate at 5 o C was 31.1 Ah with CPV vessel controlling the capacity. The charge retention for the battery in the 72-hour test was 66% (to 2V). The state of charge when the battery is trickle charged at 10 mA after a full charge at 2.3A for 16 hours was found to decrease as measured by the decrease in pressure of 242 Psi for CPV #4 and 315 psi for CPV #5.

In the 10% state of charge, trickle charging the battery at 10 mA induced a collapse in the voltage of CPV#2 to 1.4 V after 327 hours.

The test was continued with voltage clamped at the battery voltage which generated about 12-15 mA trickle charge current. The collapsed cell declined in voltage to 1.29V. In addition one other cell started to show a degrading voltage. The trickle charge rate was the increased to 115mA which improved the cell voltages slightly with no rejuvenation of the collapsed cell as shown in the figure.

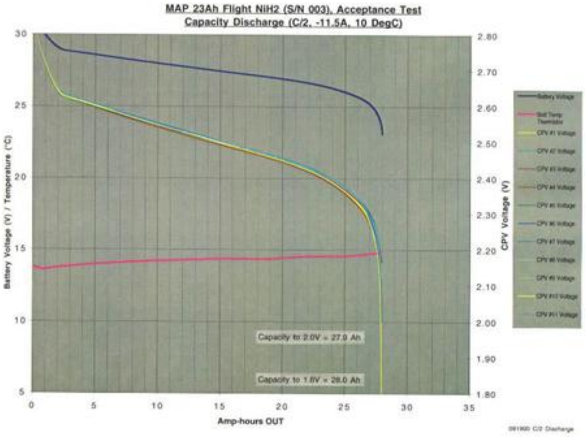
Then, the effect a short duration discharge was tested by 1.0 ampere discharge for 1 minute followed by 25 minute charge at 2.3 amperes. This procedure improved the voltage of the anomalous CPV #2 as shown in the following figures.

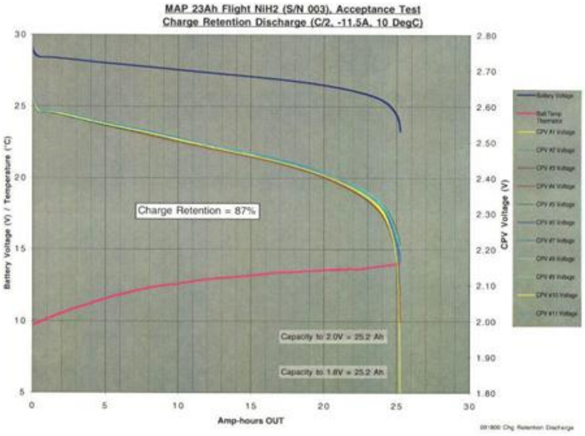
The flight spare battery was then subjected to pulse charges daily at 6 A followed by trickle charge at 115 mA. This procedure helped all the cell voltages to be in the family.



Results Summary Flow Chart

WMAP Capacity and Charge Retention Flight Battery Acceptance Test Results

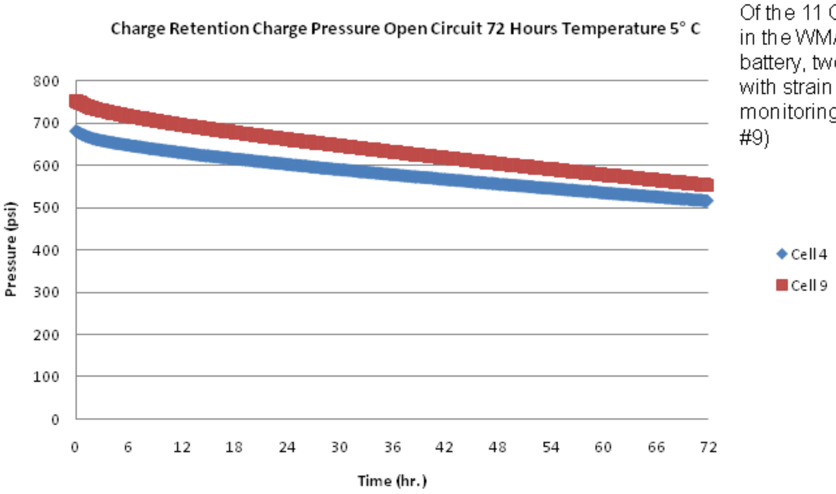




Flight Battery Acceptance testing suggests a minimum charge rate of 37.5 mA at BOL to maintain full charge.

Nominal performance noted for test results.

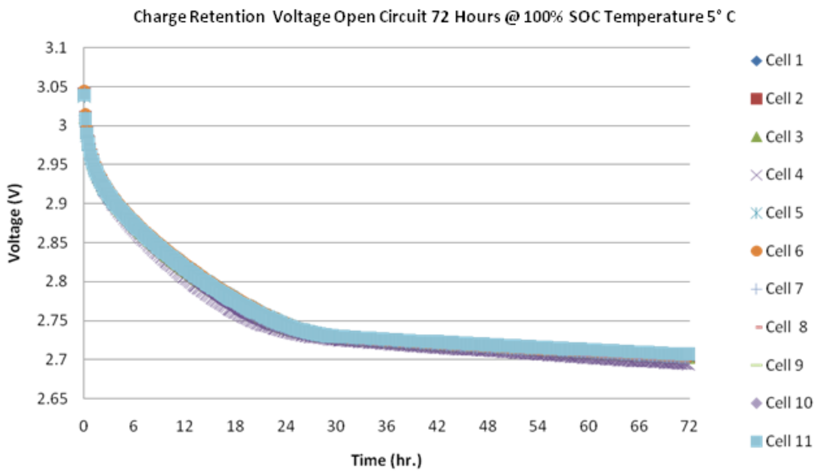
WMAP Flight Spare (Test) Battery Charge Retention Test Results- Pressure (at 5°C)



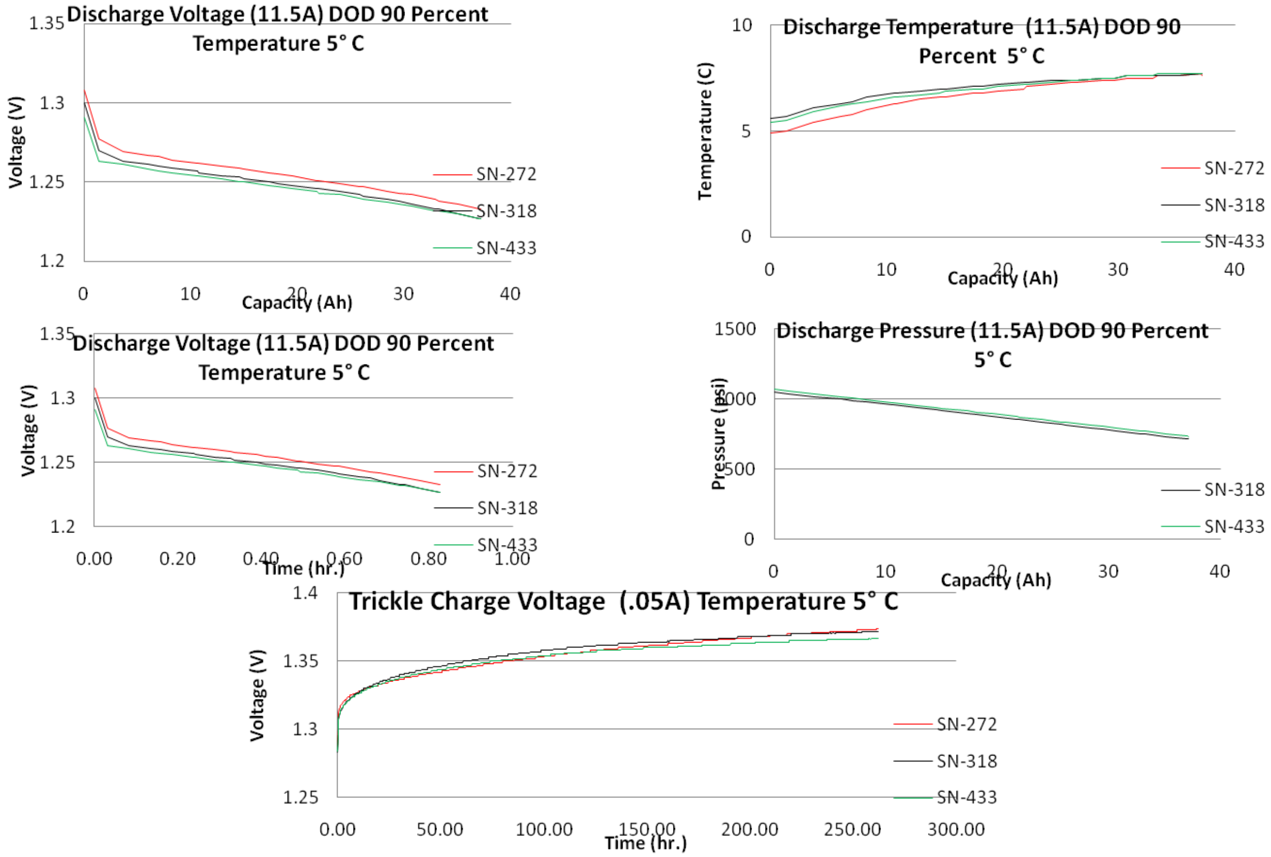
Of the 11 CPV cells, in the WMAP flight spare battery, two were equipped with strain gages for monitoring pressure (#4 and #9)

Flight spare battery indicated larger than expected rate of capacity fade during open circuit stand testing (expected approximately 10-15%) based on available strain gage measurements.

WMAP Flight Spare (Test) Battery Charge Retention Results (at 5°C)

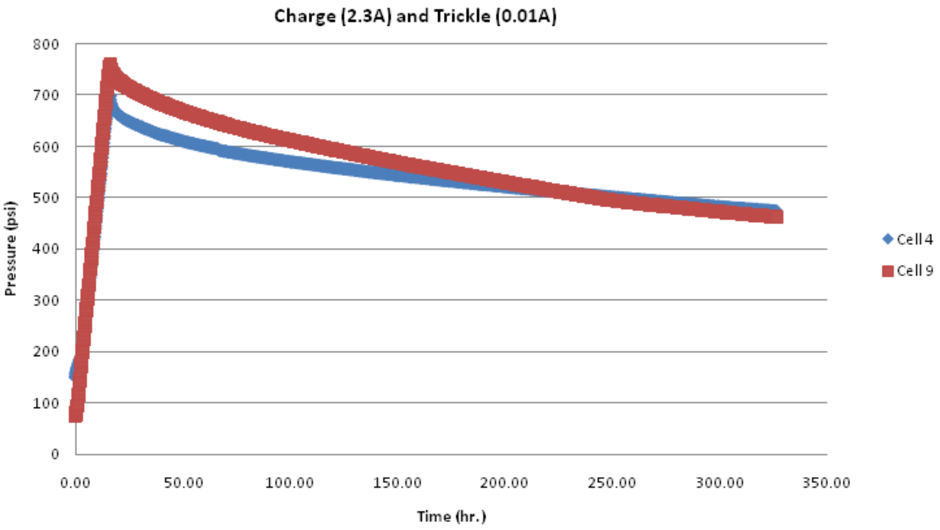


CPV voltages decreased as expected during open circuit stand, but were generally tapering to a stable performance.



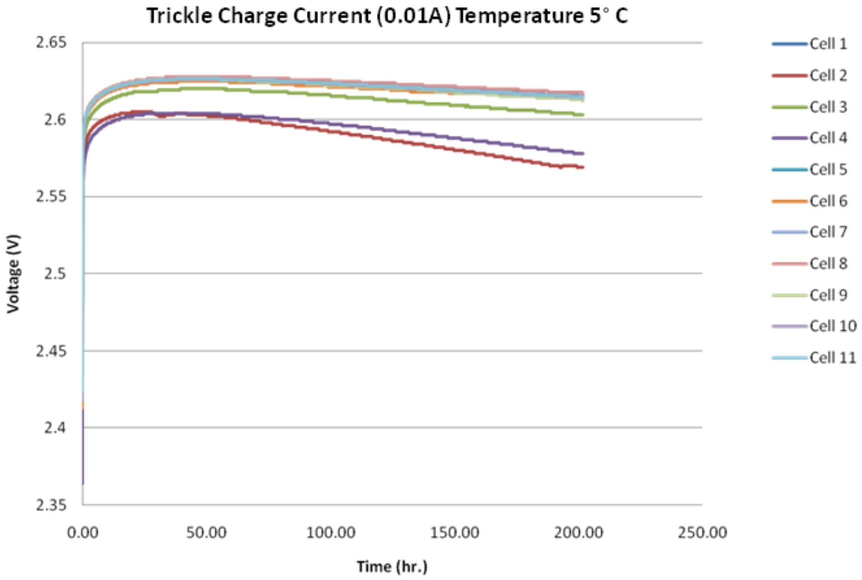
HST Sample Cell Discharge and Trickle Charge Characteristics

WMAP Flight Spare (Test) Battery Pressure (Capacity) Response Under Low Trickle Charge Rate (C/2300) at High SOC (at 5°C)



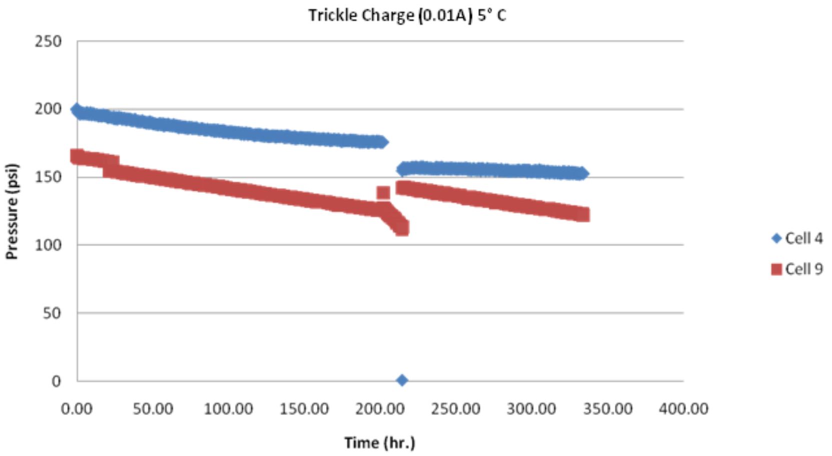
Capacity fade beginning at full state of charge and low trickle charge rate was comparable to open circuit stand results.

WMAP Flight Spare (Test) Battery Voltage Response Under Low Trickle Charge Rate (C/2300) at Low SOC (at 5°C)



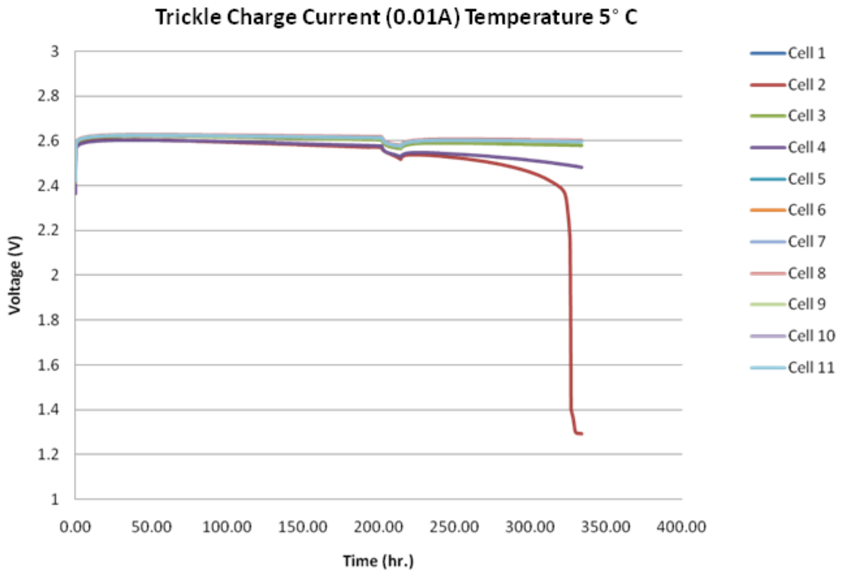
Voltage characteristics also followed comparable characteristics to open circuit stand testing with signs of divergence for several cells.

WMAP Flight Spare (Test) Battery Pressure (Capacity) Under Low Trickle Charge at Low SOC (at 5°C)



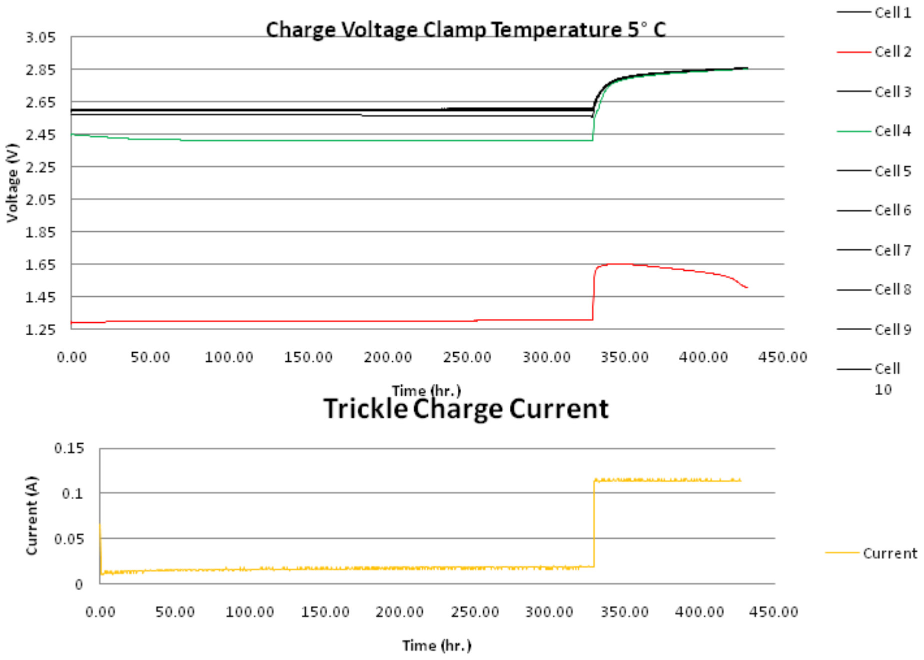
After reducing state of charge to roughly 10% of capacity, pressure (capacity) continued to fall using low trickle charge rate (discontinuities due to strain gage anomalies).

WMAP Flight Spare (Test) Battery Voltage Under Simulated On-Orbit Low Trickle Charge (C/2300) at Low SOC (at 5°C)

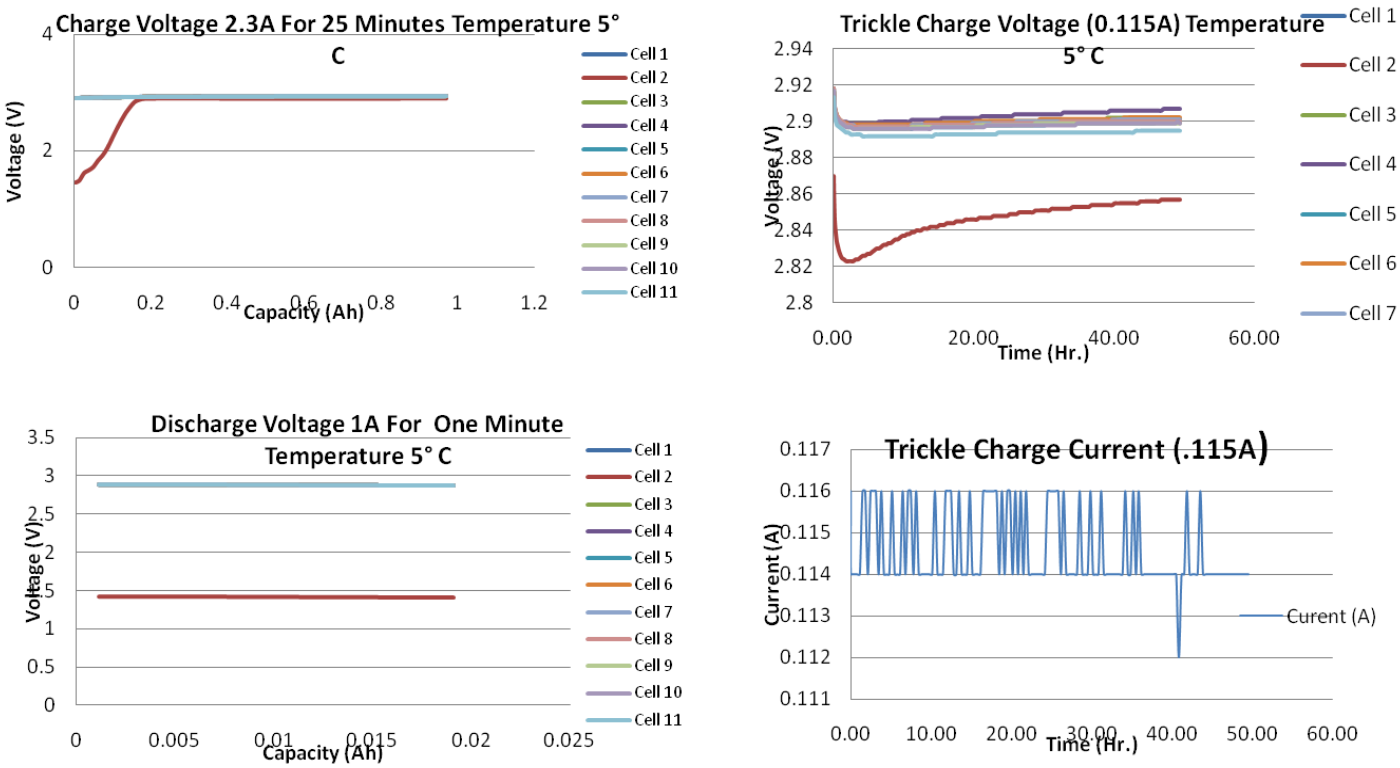


Simulated on-orbit conditions successfully duplicated a cell voltage collapse while using low trickle charge conditions similar to that experienced on-orbit.

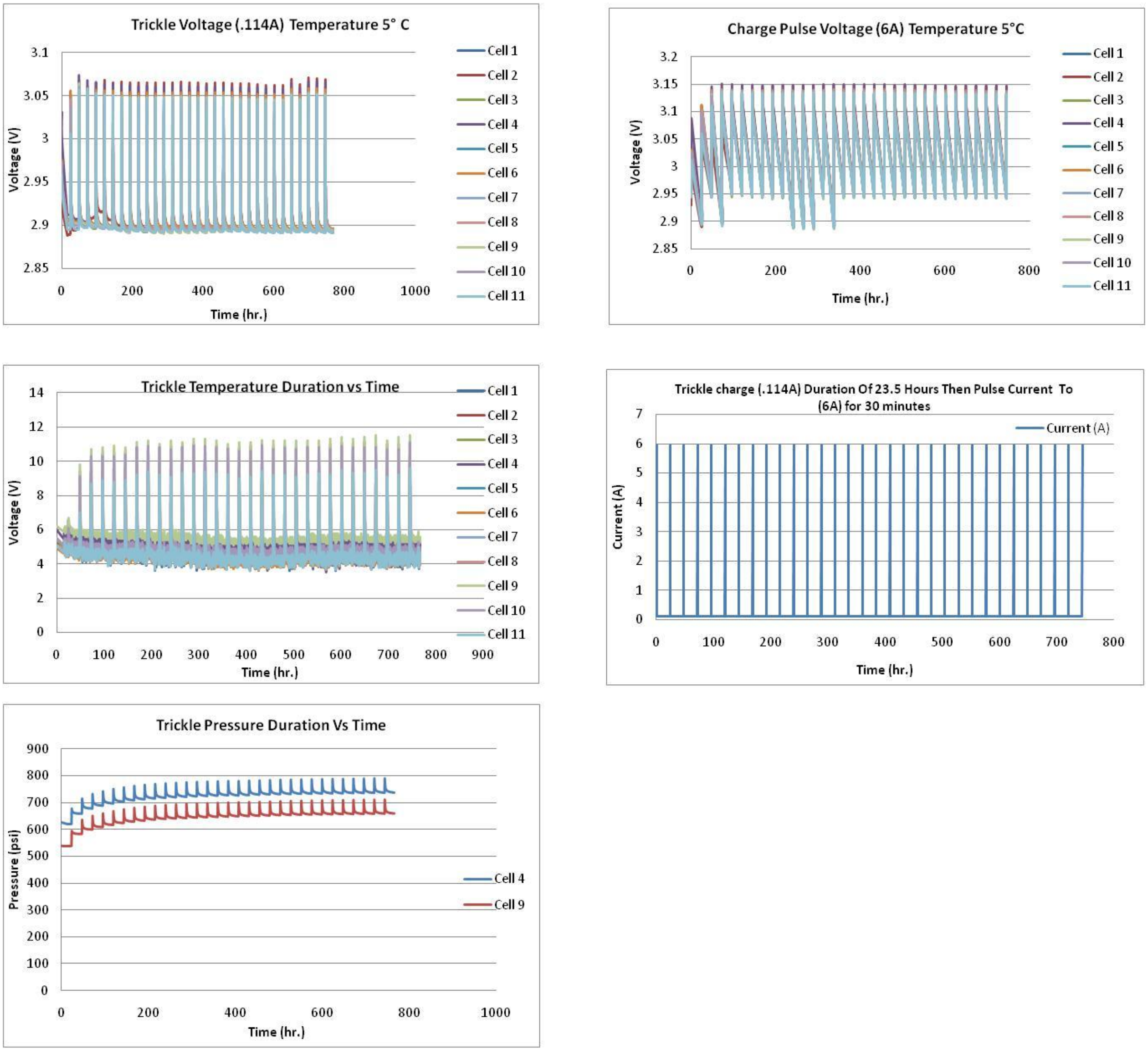
Flight Spare (Test) Battery Switch from Voltage Clamp to Fixed Trickle Charge (C/200)



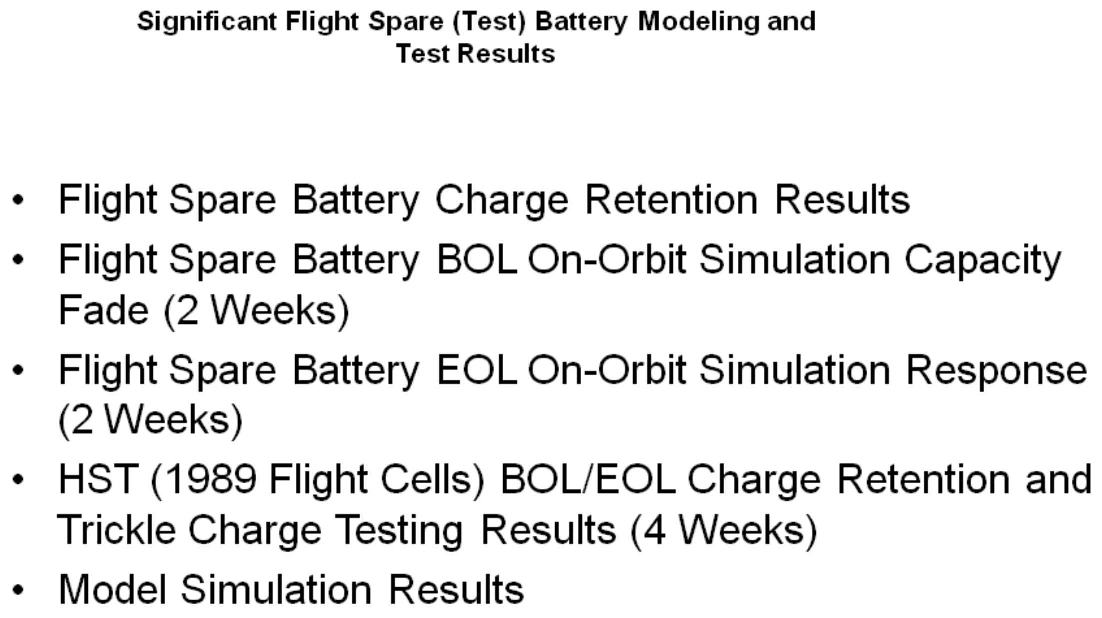
Similar to the on-orbit experience, when just the trickle charge rate was increased there were initial benefits but soon after more divergence occurs.



Discharge/Charge Test Results



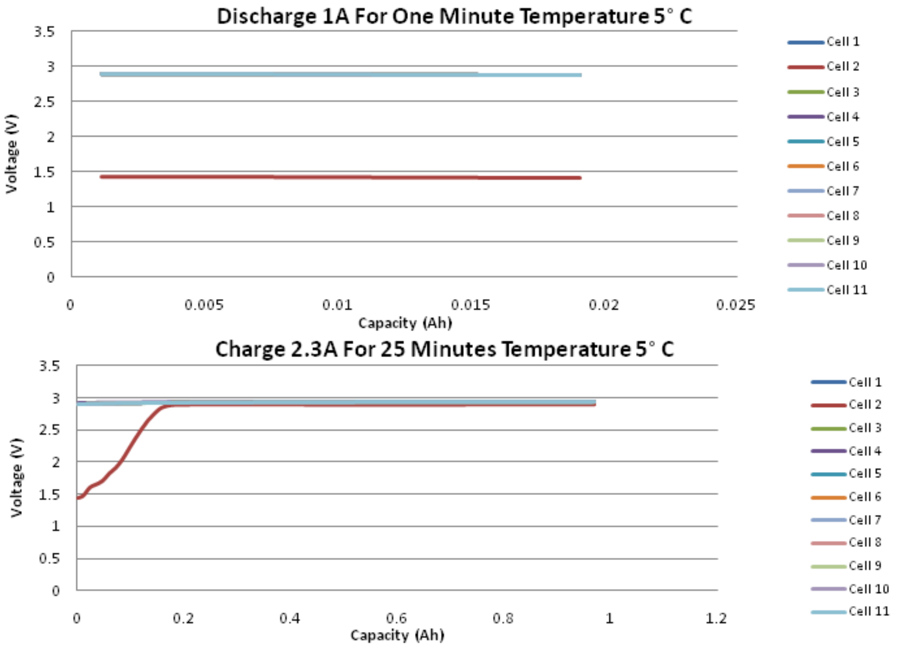
Response of the Battery to Daily Pulse Charging at 6A



Significant Flight Spare (Test) Battery Modeling and Test Results

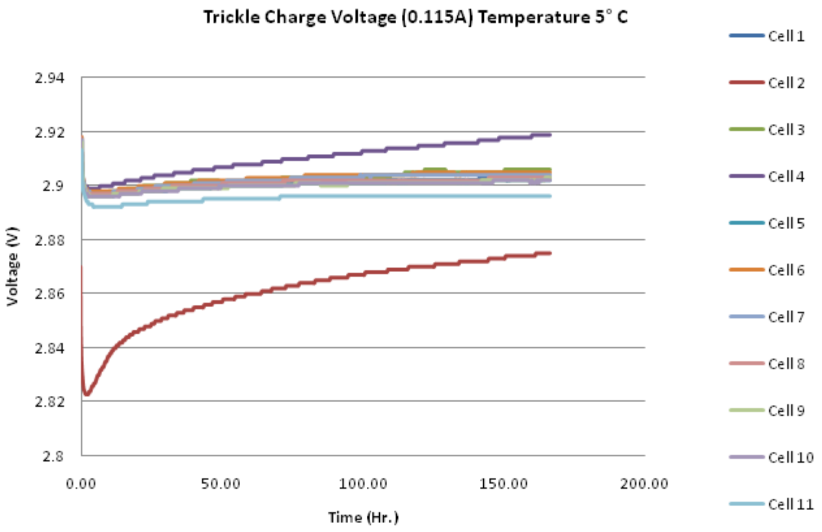
- Flight Spare Battery Charge Retention Results
- Flight Spare Battery BOL On-Orbit Simulation Capacity Fade (2 Weeks)
- Flight Spare Battery EOL On-Orbit Simulation Response (2 Weeks)
- HST (1989 Flight Cells) BOL/EOL Charge Retention and Trickle Charge Testing Results (4 Weeks)
- Model Simulation Results

Flight Spare (Test) Battery Response to Discharge/Charge Cycle



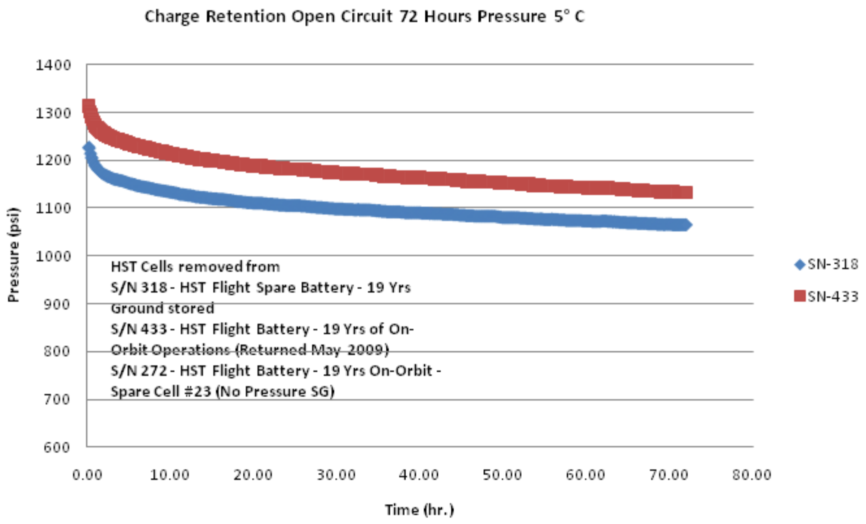
Small discharge followed by a C/10 charge in the test battery recovered the collapsed cell.

Flight Spare (Test) Battery Response Post Discharge/Charge Cycle



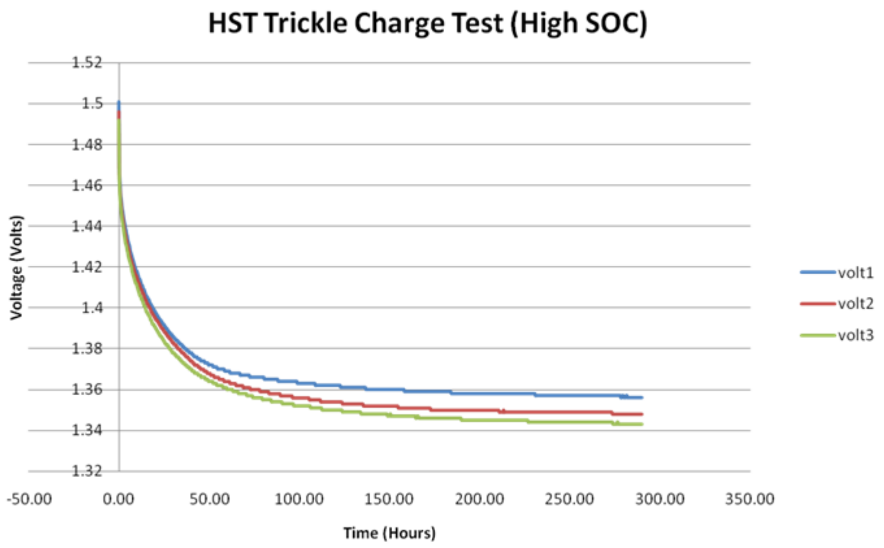
Previously collapsed cell has been recovering to near normal while voltage divergence is also being experienced.

Comparison Sample HST (aged cells) Charge Retention Test Results (at 5°C)



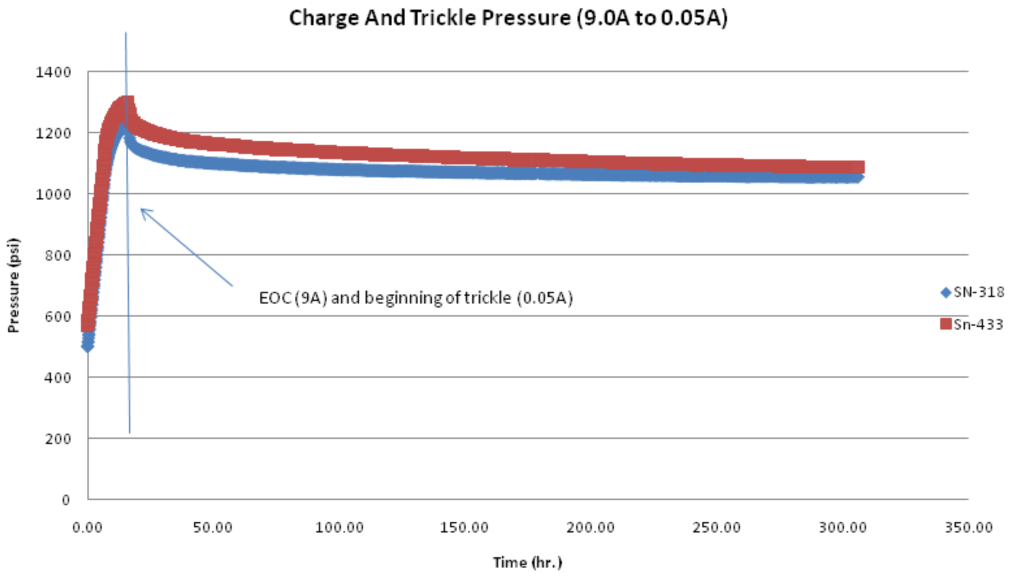
Open circuit stand pressure response of selected 1989 HST cells for comparison.

Comparison Sample HST (aged cells) Voltage Test Results High SOC/Low Trickle Charge (at 5°C)

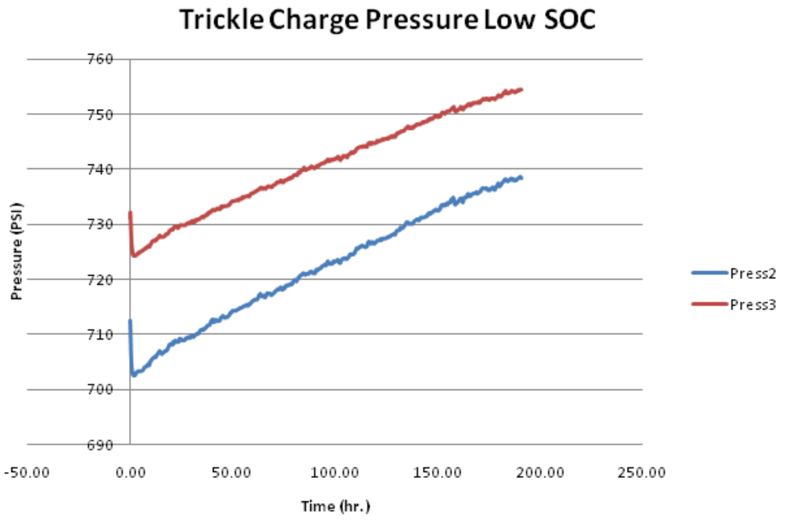


HST cell voltages stabilized under simulated low trickle charge testing at high SOC.

HST Sample Cells High SOC and Low Trickle Charge Rate (at 5°C)

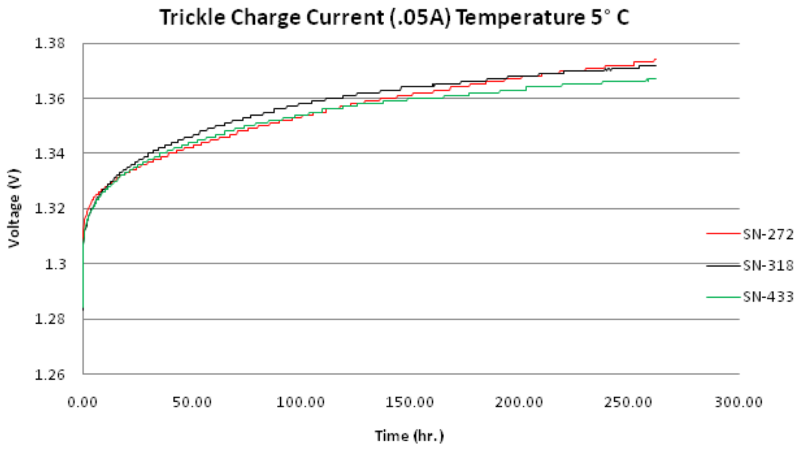


Low SOC Low Trickle Charge Test Results on HST Cells - Pressure (Capacity) (at 5°C)

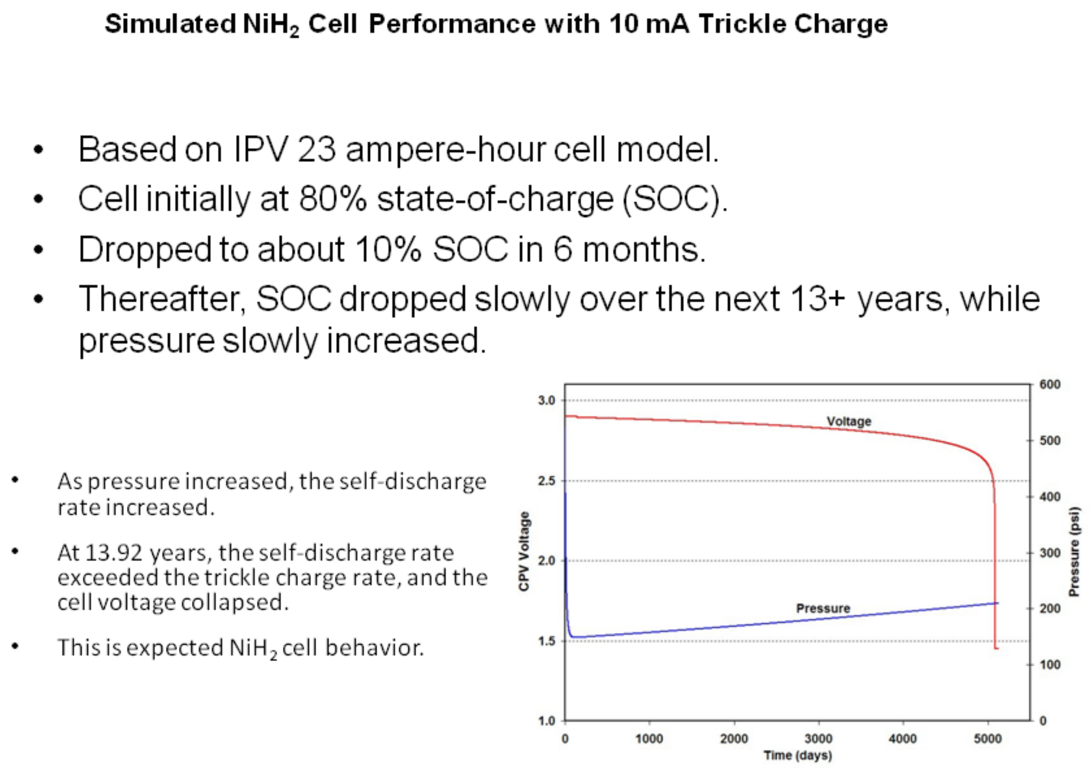


Unlike WMAP test battery, after lowering state of charge to 10%, pressure increased in HST cells while subjected to low trickle charge rate (indicating charging).

Low SOC Low Trickle Charge Test Results on HST Cells – Voltage (at 5°C)



Also unlike WMAP test battery, after lowering state of charge to 10%, voltage also recovered on sample HST cells while subjected to low trickle charge rate.

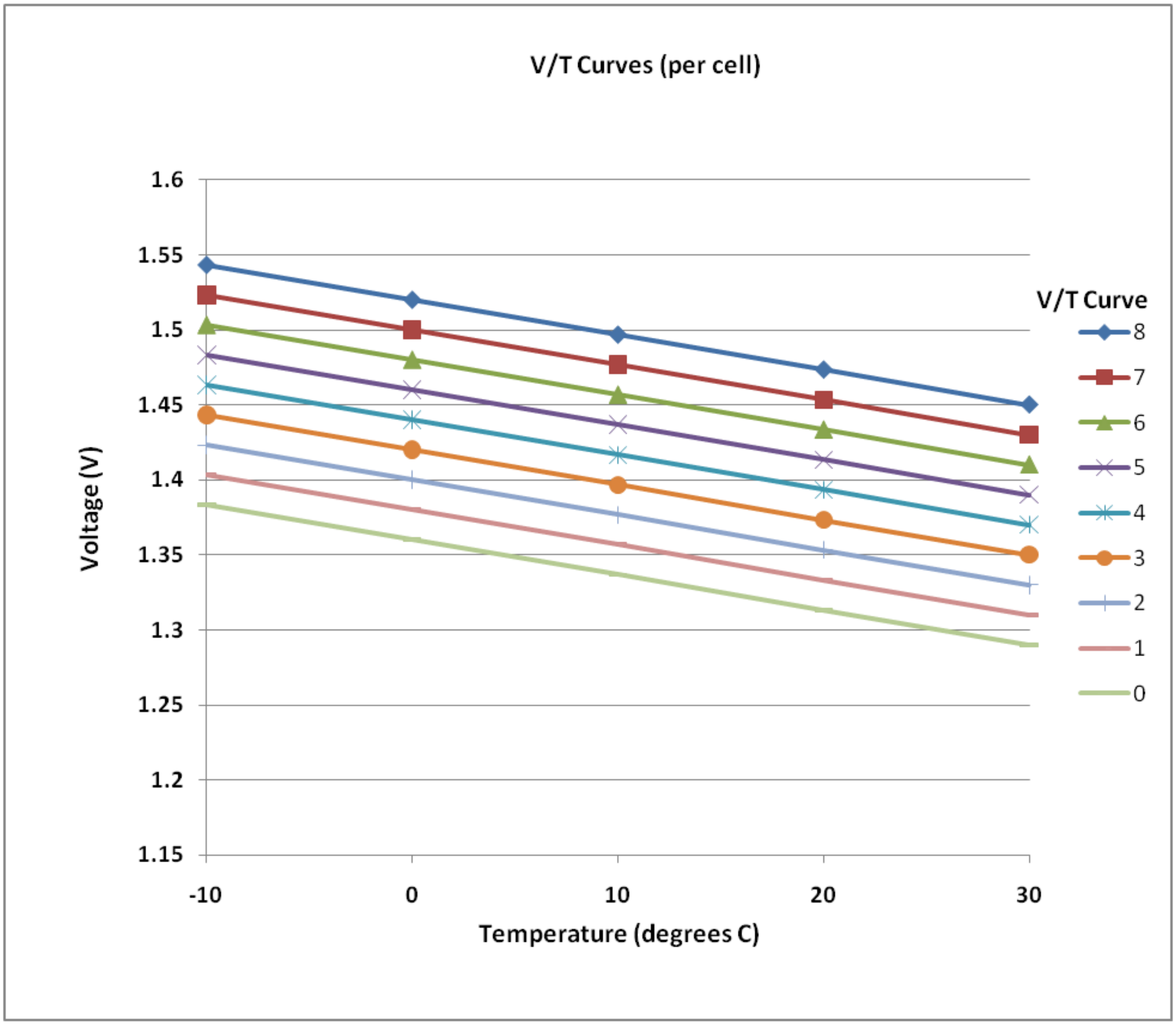


Simulated NiH_2 Cell Performance with 10 mA Trickle Charge

- Based on IPV 23 ampere-hour cell model.
- Cell initially at 80% state-of-charge (SOC).
- Dropped to about 10% SOC in 6 months.
- Thereafter, SOC dropped slowly over the next 13+ years, while pressure slowly increased.

- As pressure increased, the self-discharge rate increased.
- At 13.92 years, the self-discharge rate exceeded the trickle charge rate, and the cell voltage collapsed.
- This is expected NiH_2 cell behavior.

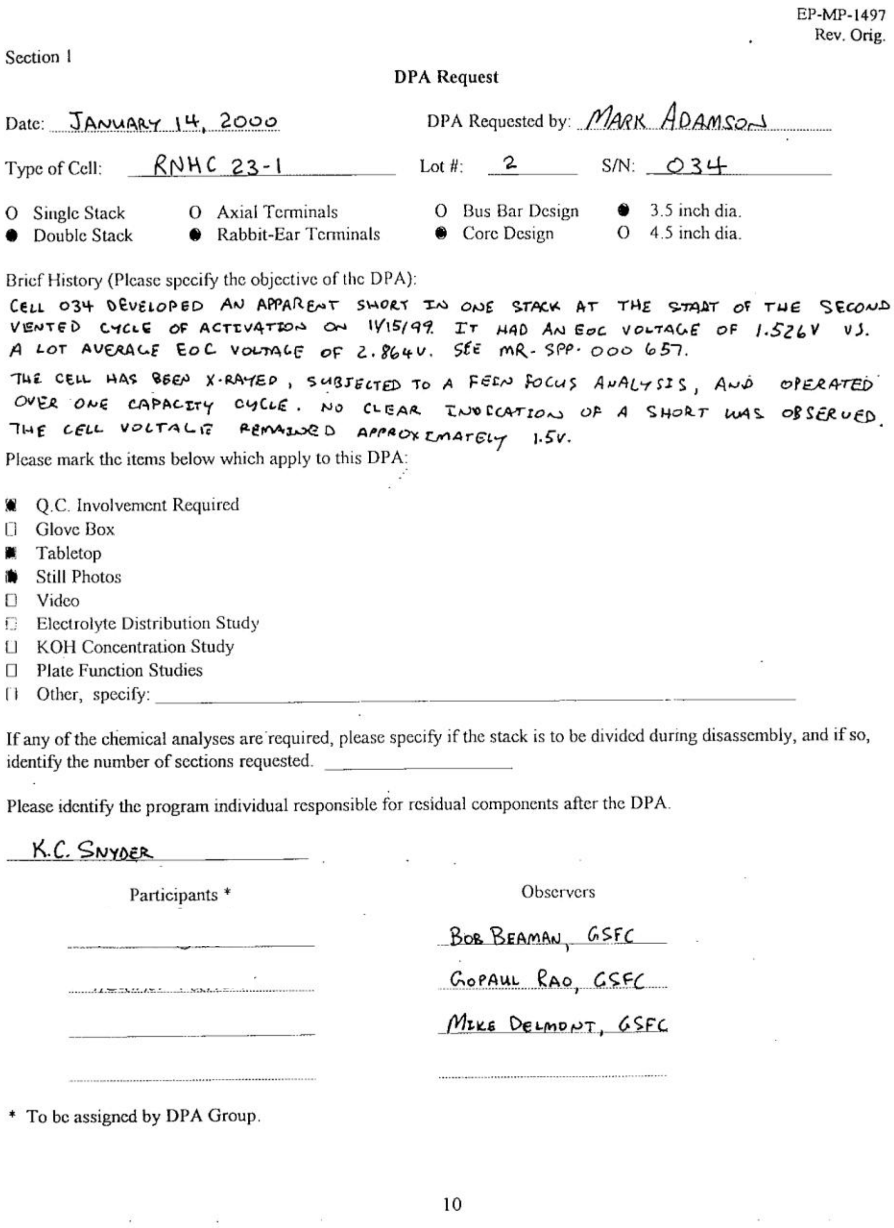
Appendix D. Standard V/T Curve Definitions



Standard temperature compensated voltage curves for NiH_2 cells.

The graph above represents a standard set of temperature compensated voltage curves typically used for NiH2 cells. As is the case for most applications, the curves are programmed into software control algorithms as a slope and intercept equation that can be changed as needed to accommodate the conditions required. To achieve the comparable V/T curve for an entire battery the values provided would be multiplied by the number of cells in the battery (e.g., for a 22 cell battery a V/T level of 3 at 0 degrees C would be 22*1.42V=31.24V.)

Appendix E. DPA Failed Cell during Activation at EPT



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Section 1

DPA Request

Date: JANUARY 14, 2000 DPA Requested by: MARK ADAMSON

Type of Cell: RNHC 23-1 Lot #: 2 S/N: 034

○ Single Stack ○ Axial Terminals ○ Bus Bar Design ● 3.5 inch dia.
● Double Stack ● Rabbit-Ear Terminals ● Core Design ○ 4.5 inch dia.

Brief History (Please specify the objective of the DPA):

CELL 034 DEVELOPED AN APPARENT SHORT IN ONE STACK AT THE START OF THE SECOND VENTED CYCLE OF ACTIVATION ON 11/15/99. IT HAD AN EOC VOLTAGE OF 1.526V VS. A LOT AVERAGE EOC VOLTAGE OF 2.864V. SEE MR-SPP-000 657.

THE CELL HAS BEEN X-RAYED, SUBJECTED TO A FEIN FOCUS ANALYSIS, AND OPERATED OVER ONE CAPACITY CYCLE. NO CLEAR INDICATION OF A SHORT WAS OBSERVED. THE CELL VOLTAGE REMAINED APPROXIMATELY 1.5V.

Please mark the items below which apply to this DPA:

- ☒ Q.C. Involvement Required
- ☐ Glove Box
- ☒ Tabletop
- ☒ Still Photos
- ☐ Video
- ☐ Electrolyte Distribution Study
- ☐ KOH Concentration Study
- ☐ Plate Function Studies
- ☐ Other, specify: ____

If any of the chemical analyses are required, please specify if the stack is to be divided during disassembly, and if so, identify the number of sections requested. ____

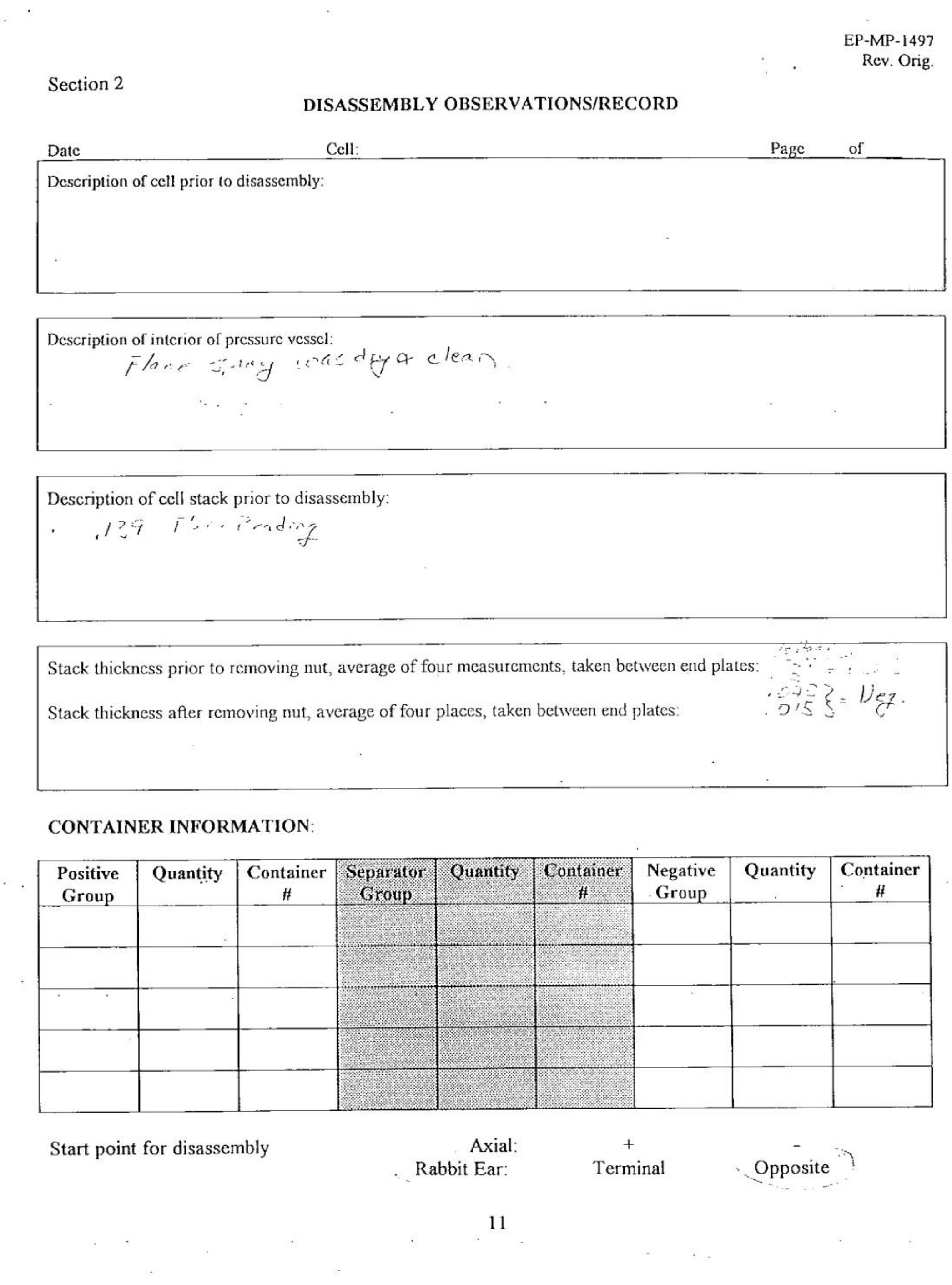
Please identify the program individual responsible for residual components after the DPA.

K.C. SNYDER

Participants *	Observers
	BOB BEAMAN, GSFC
	GOPAUL RAO, GSFC
	MIKE DELMONT, GSFC

* To be assigned by DPA Group.

10



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Section 2

DISASSEMBLY OBSERVATIONS/RECORD

Date Cell: Page of

Description of cell prior to disassembly:

Description of interior of pressure vessel:
Flame spray was dry & clean.

Description of cell stack prior to disassembly:
.129 Flare Reading

Stack thickness prior to removing nut, average of four measurements, taken between end plates: [illegible]

Stack thickness after removing nut, average of four places, taken between end plates:
.042 }
.015 } = Deg.

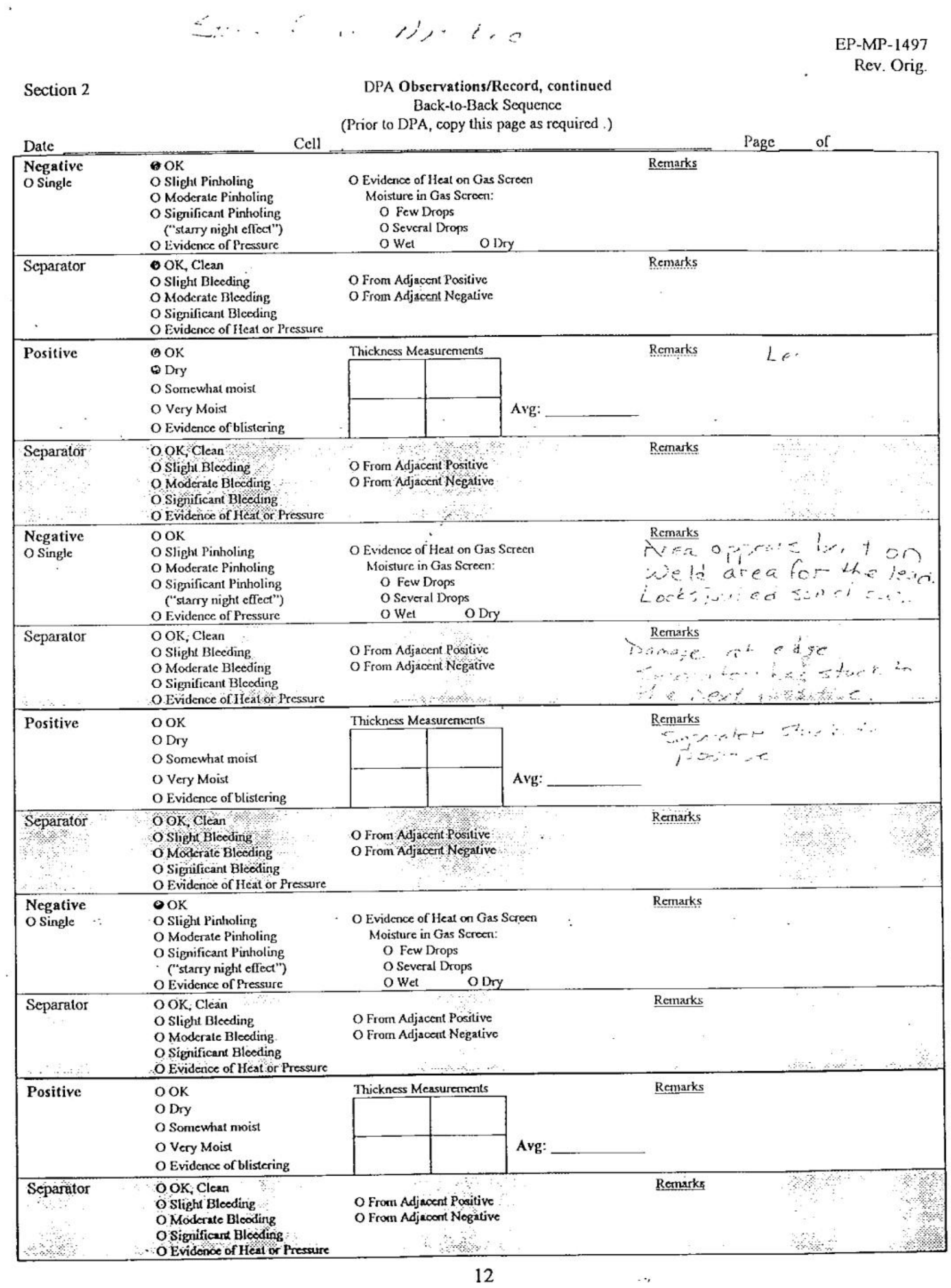
CONTAINER INFORMATION:

Positive Group	Quantity	Container #	Separator Group	Quantity	Container #	Negative Group	Quantity	Container #

Start point for disassembly

Axial: + -
Rabbit Ear: Terminal [✓ Opposite]

11



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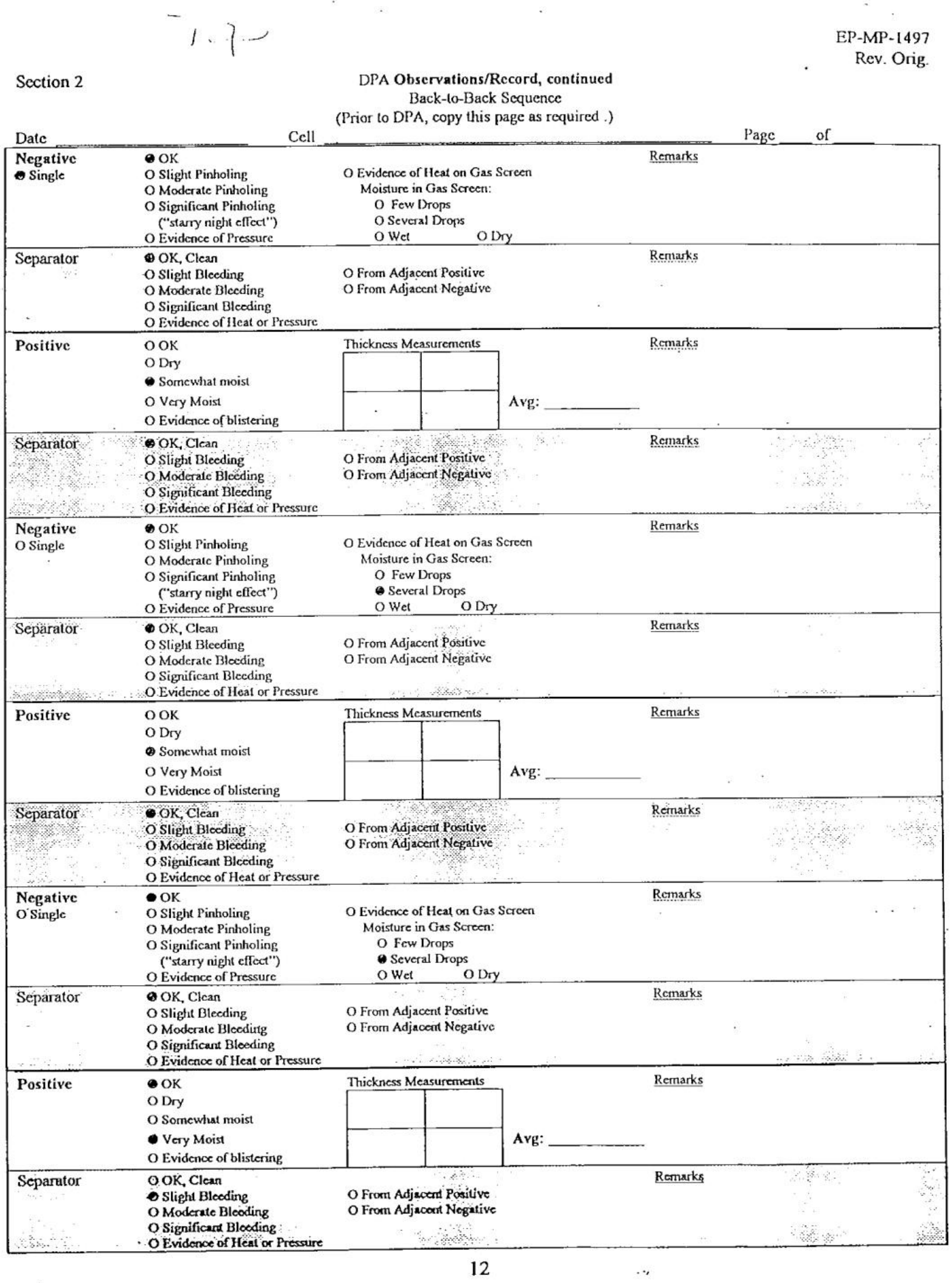
Section 2

DPA **Observations/Record, continued**
Back-to-Back Sequence
(Prior to DPA, copy this page as required .)

Date ____________ Cell ____________ Page ____ of ____

Negative ○ Single	● OK ○ Slight Pinholing ○ Moderate Pinholing ○ Significant Pinholing ("starry night effect") ○ Evidence of Pressure	○ Evidence of Heat on Gas Screen Moisture in Gas Screen: ○ Few Drops ○ Several Drops ○ Wet ○ Dry	Remarks
Separator	● OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Positive	● OK ● Dry ○ Somewhat moist ○ Very Moist ○ Evidence of blistering	Thickness Measurements Avg: ________	Remarks Le
Separator	○ OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Negative ○ Single	○ OK ○ Slight Pinholing ○ Moderate Pinholing ○ Significant Pinholing ("starry night effect") ○ Evidence of Pressure	○ Evidence of Heat on Gas Screen Moisture in Gas Screen: ○ Few Drops ○ Several Drops ○ Wet ○ Dry	Remarks Area opposite [illegible] on weld area for the lead. Looks [illegible]
Separator	○ OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks Damage at edge Separator has stuck to the next positive.
Positive	○ OK ○ Dry ○ Somewhat moist ○ Very Moist ○ Evidence of blistering	Thickness Measurements Avg: ________	Remarks Separator stuck to Positive
Separator	○ OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Negative ○ Single	● OK ○ Slight Pinholing ○ Moderate Pinholing ○ Significant Pinholing ("starry night effect") ○ Evidence of Pressure	○ Evidence of Heat on Gas Screen Moisture in Gas Screen: ○ Few Drops ○ Several Drops ○ Wet ○ Dry	Remarks
Separator	○ OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Positive	○ OK ○ Dry ○ Somewhat moist ○ Very Moist ○ Evidence of blistering	Thickness Measurements Avg: ________	Remarks
Separator	○ OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks

12



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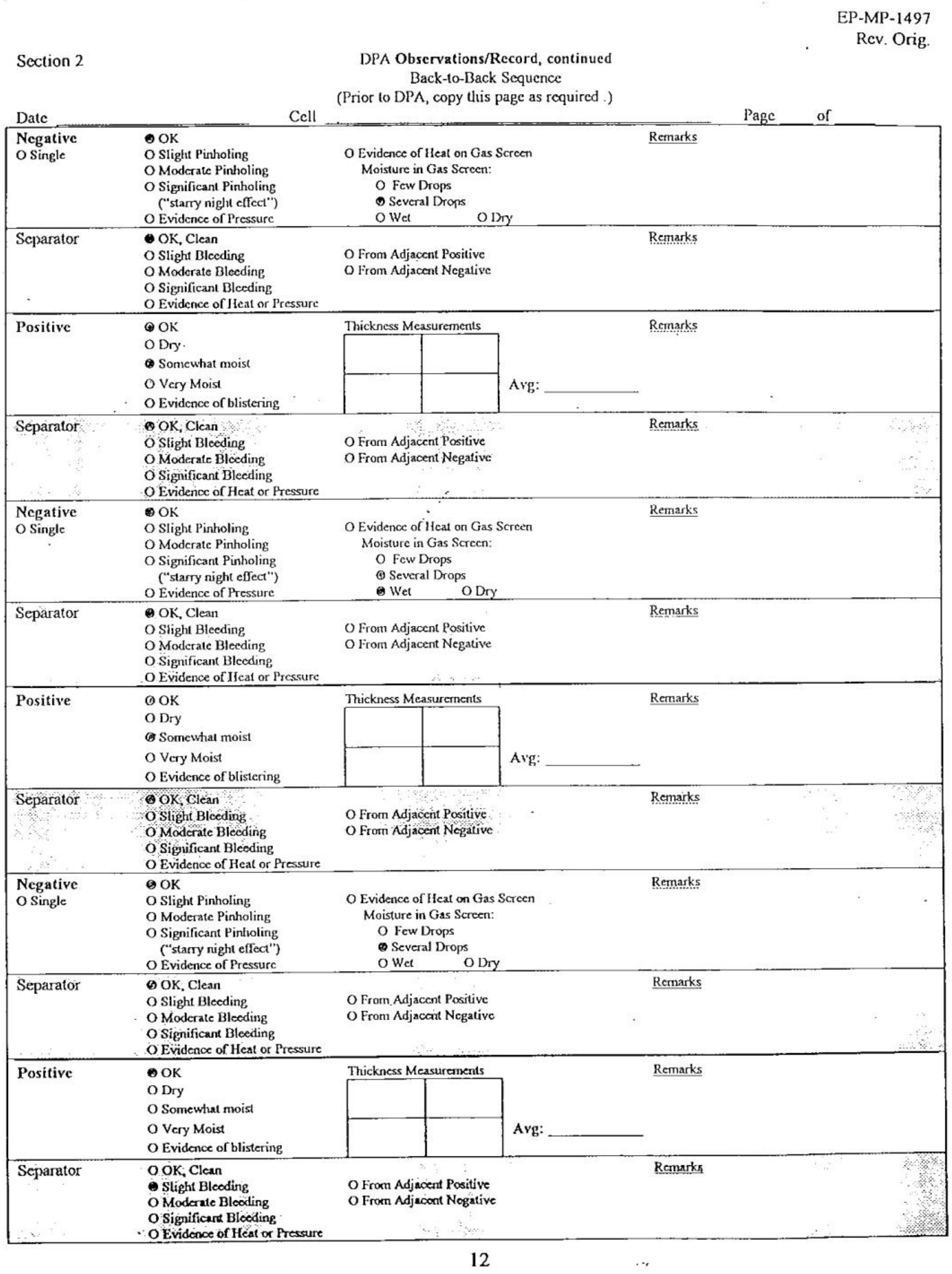
Section 2

DPA **Observations/Record, continued**
Back-to-Back Sequence
(Prior to DPA, copy this page as required .)

Date ____________ Cell ____________ Page ____ of ____

Negative ● Single	● OK ○ Slight Pinholing ○ Moderate Pinholing ○ Significant Pinholing ("starry night effect") ○ Evidence of Pressure	○ Evidence of Heat on Gas Screen Moisture in Gas Screen: ○ Few Drops ○ Several Drops ○ Wet ○ Dry	Remarks
Separator	● OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Positive	○ OK ○ Dry ● Somewhat moist ○ Very Moist ○ Evidence of blistering	Thickness Measurements Avg: ________	Remarks
Separator	● OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Negative ○ Single	● OK ○ Slight Pinholing ○ Moderate Pinholing ○ Significant Pinholing ("starry night effect") ○ Evidence of Pressure	○ Evidence of Heat on Gas Screen Moisture in Gas Screen: ○ Few Drops ● Several Drops ○ Wet ○ Dry	Remarks
Separator	● OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Positive	○ OK ○ Dry ● Somewhat moist ○ Very Moist ○ Evidence of blistering	Thickness Measurements Avg: ________	Remarks
Separator	● OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Negative ○ Single	● OK ○ Slight Pinholing ○ Moderate Pinholing ○ Significant Pinholing ("starry night effect") ○ Evidence of Pressure	○ Evidence of Heat on Gas Screen Moisture in Gas Screen: ○ Few Drops ● Several Drops ○ Wet ○ Dry	Remarks
Separator	● OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Positive	● OK ○ Dry ○ Somewhat moist ● Very Moist ○ Evidence of blistering	Thickness Measurements Avg: ________	Remarks
Separator	○ OK, Clean ● Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks

12



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Section 2

DPA **Observations/Record, continued**
Back-to-Back Sequence
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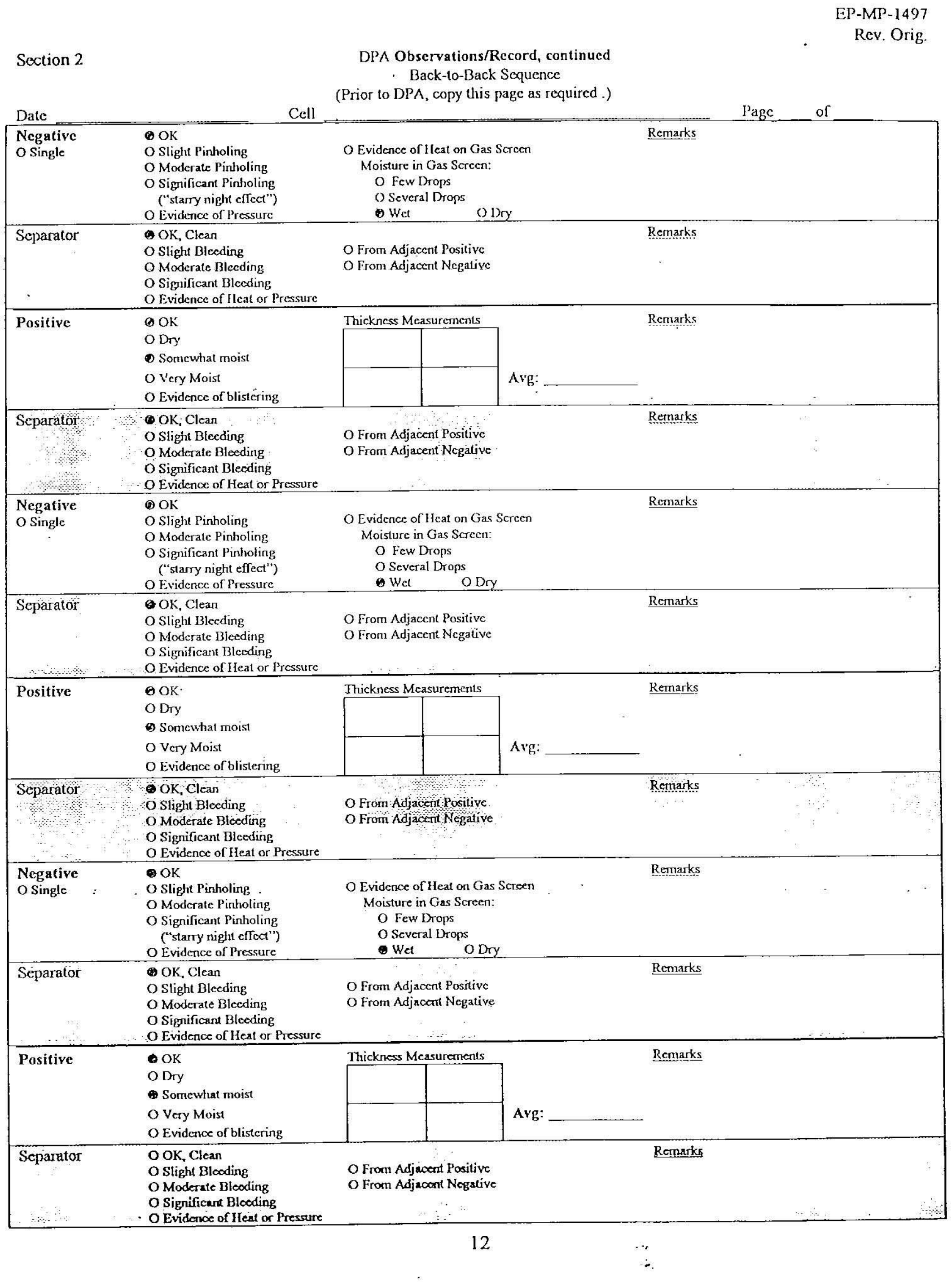
Date ____________ Cell ____________ Page ____ of ____

Negative ○ Single	● OK ○ Slight Pinholing ○ Moderate Pinholing ○ Significant Pinholing ("starry night effect") ○ Evidence of Pressure	○ Evidence of Heat on Gas Screen Moisture in Gas Screen: ○ Few Drops ● Several Drops ○ Wet ○ Dry	Remarks
Separator	● OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Positive	● OK ○ Dry ● Somewhat moist ○ Very Moist ○ Evidence of blistering	Thickness Measurements Avg: ____________	Remarks
Separator	● OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Negative ○ Single	● OK ○ Slight Pinholing ○ Moderate Pinholing ○ Significant Pinholing ("starry night effect") ○ Evidence of Pressure	○ Evidence of Heat on Gas Screen Moisture in Gas Screen: ○ Few Drops ● Several Drops ● Wet ○ Dry	Remarks
Separator	● OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Positive	● OK ○ Dry ● Somewhat moist ○ Very Moist ○ Evidence of blistering	Thickness Measurements Avg: ____________	Remarks
Separator	● OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Negative ○ Single	● OK ○ Slight Pinholing ○ Moderate Pinholing ○ Significant Pinholing ("starry night effect") ○ Evidence of Pressure	○ Evidence of Heat on Gas Screen Moisture in Gas Screen: ○ Few Drops ● Several Drops ○ Wet ○ Dry	Remarks
Separator	● OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Positive	● OK ○ Dry ○ Somewhat moist ○ Very Moist ○ Evidence of blistering	Thickness Measurements Avg: ____________	Remarks
Separator	○ OK, Clean ● Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks



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Section 2

DPA Observations/Record, continued
Back-to-Back Sequence
(Prior to DPA, copy this page as required .)

Date ______________ Cell ______________ Page ____ of ____

Negative
○ Single
● OK
○ Slight Pinholing
○ Moderate Pinholing
○ Significant Pinholing
("starry night effect")
○ Evidence of Pressure
○ Evidence of Heat on Gas Screen
Moisture in Gas Screen:
○ Few Drops
○ Several Drops
● Wet ○ Dry
Remarks

Separator
● OK, Clean
○ Slight Bleeding
○ Moderate Bleeding
○ Significant Bleeding
○ Evidence of Heat or Pressure
○ From Adjacent Positive
○ From Adjacent Negative
Remarks

Positive
● OK
○ Dry
● Somewhat moist
○ Very Moist
○ Evidence of blistering
Thickness Measurements
Avg: ____________
Remarks

Separator
● OK, Clean
○ Slight Bleeding
○ Moderate Bleeding
○ Significant Bleeding
○ Evidence of Heat or Pressure
○ From Adjacent Positive
○ From Adjacent Negative
Remarks

Negative
○ Single
● OK
○ Slight Pinholing
○ Moderate Pinholing
○ Significant Pinholing
("starry night effect")
○ Evidence of Pressure
○ Evidence of Heat on Gas Screen
Moisture in Gas Screen:
○ Few Drops
○ Several Drops
● Wet ○ Dry
Remarks

Separator
● OK, Clean
○ Slight Bleeding
○ Moderate Bleeding
○ Significant Bleeding
○ Evidence of Heat or Pressure
○ From Adjacent Positive
○ From Adjacent Negative
Remarks

Positive
● OK
○ Dry
● Somewhat moist
○ Very Moist
○ Evidence of blistering
Thickness Measurements
Avg: ____________
Remarks

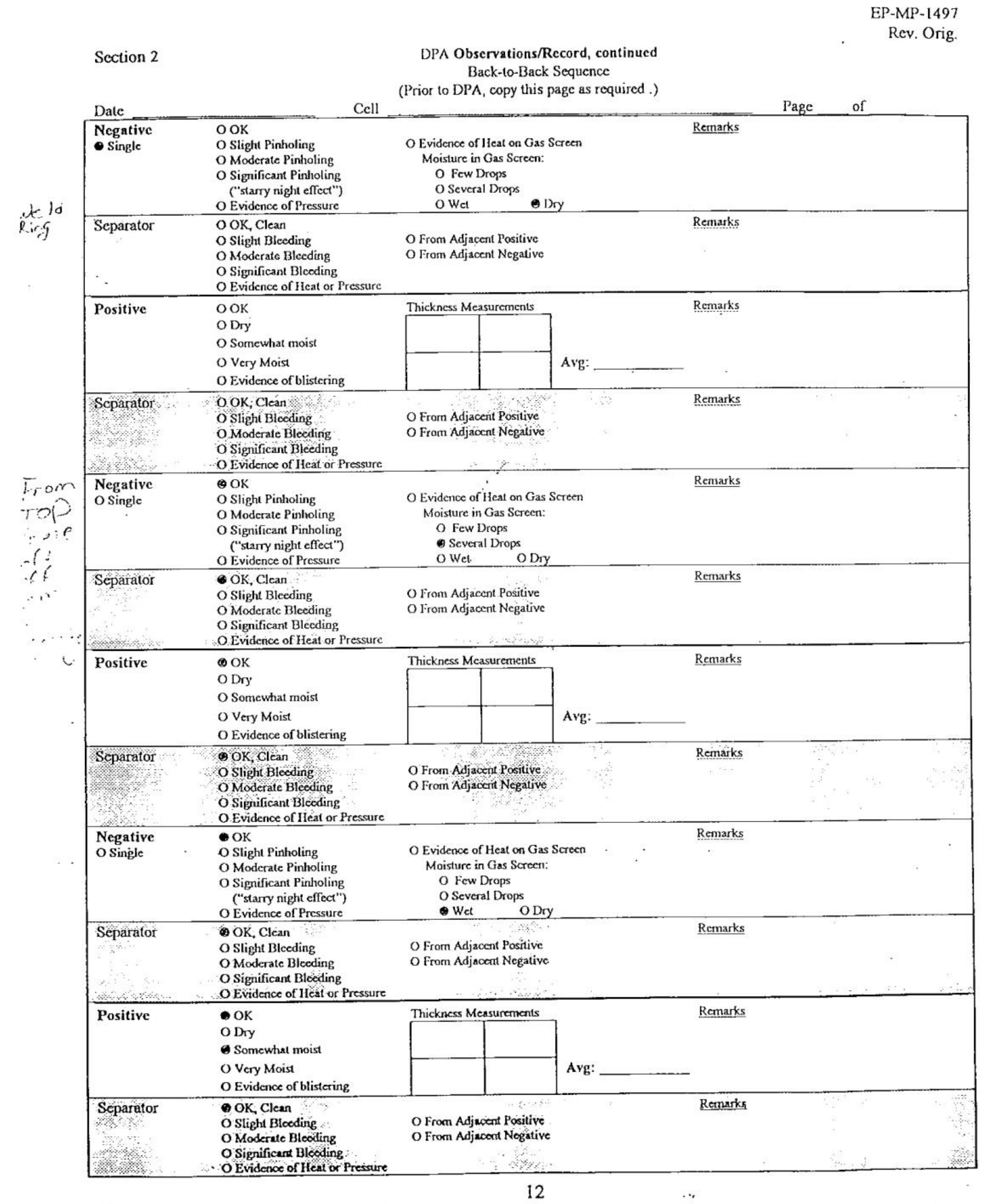
Separator
● OK, Clean
○ Slight Bleeding
○ Moderate Bleeding
○ Significant Bleeding
○ Evidence of Heat or Pressure
○ From Adjacent Positive
○ From Adjacent Negative
Remarks

Negative
○ Single
● OK
○ Slight Pinholing
○ Moderate Pinholing
○ Significant Pinholing
("starry night effect")
○ Evidence of Pressure
○ Evidence of Heat on Gas Screen
Moisture in Gas Screen:
○ Few Drops
○ Several Drops
● Wet ○ Dry
Remarks

Separator
● OK, Clean
○ Slight Bleeding
○ Moderate Bleeding
○ Significant Bleeding
○ Evidence of Heat or Pressure
○ From Adjacent Positive
○ From Adjacent Negative
Remarks

Positive
● OK
○ Dry
● Somewhat moist
○ Very Moist
○ Evidence of blistering
Thickness Measurements
Avg: ____________
Remarks

Separator
○ OK, Clean
○ Slight Bleeding
○ Moderate Bleeding
○ Significant Bleeding
○ Evidence of Heat or Pressure
○ From Adjacent Positive
○ From Adjacent Negative
Remarks



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Section 2

DPA **Observations/Record, continued**
Back-to-Back Sequence
(Prior to DPA, copy this page as required .)

Date ______ Cell ______ Page ___ of

Weld Ring

From TOP [illegible]

Negative ● Single	○ OK ○ Slight Pinholing ○ Moderate Pinholing ○ Significant Pinholing ("starry night effect") ○ Evidence of Pressure	○ Evidence of Heat on Gas Screen Moisture in Gas Screen: ○ Few Drops ○ Several Drops ○ Wet ● Dry	Remarks
Separator	○ OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
Positive	○ OK ○ Dry ○ Somewhat moist ○ Very Moist ○ Evidence of blistering	Thickness Measurements Avg: ______	Remarks
Separator	○ OK, Clean ○ Slight Bleeding ○ Moderate Bleeding ○ Significant Bleeding ○ Evidence of Heat or Pressure	○ From Adjacent Positive ○ From Adjacent Negative	Remarks
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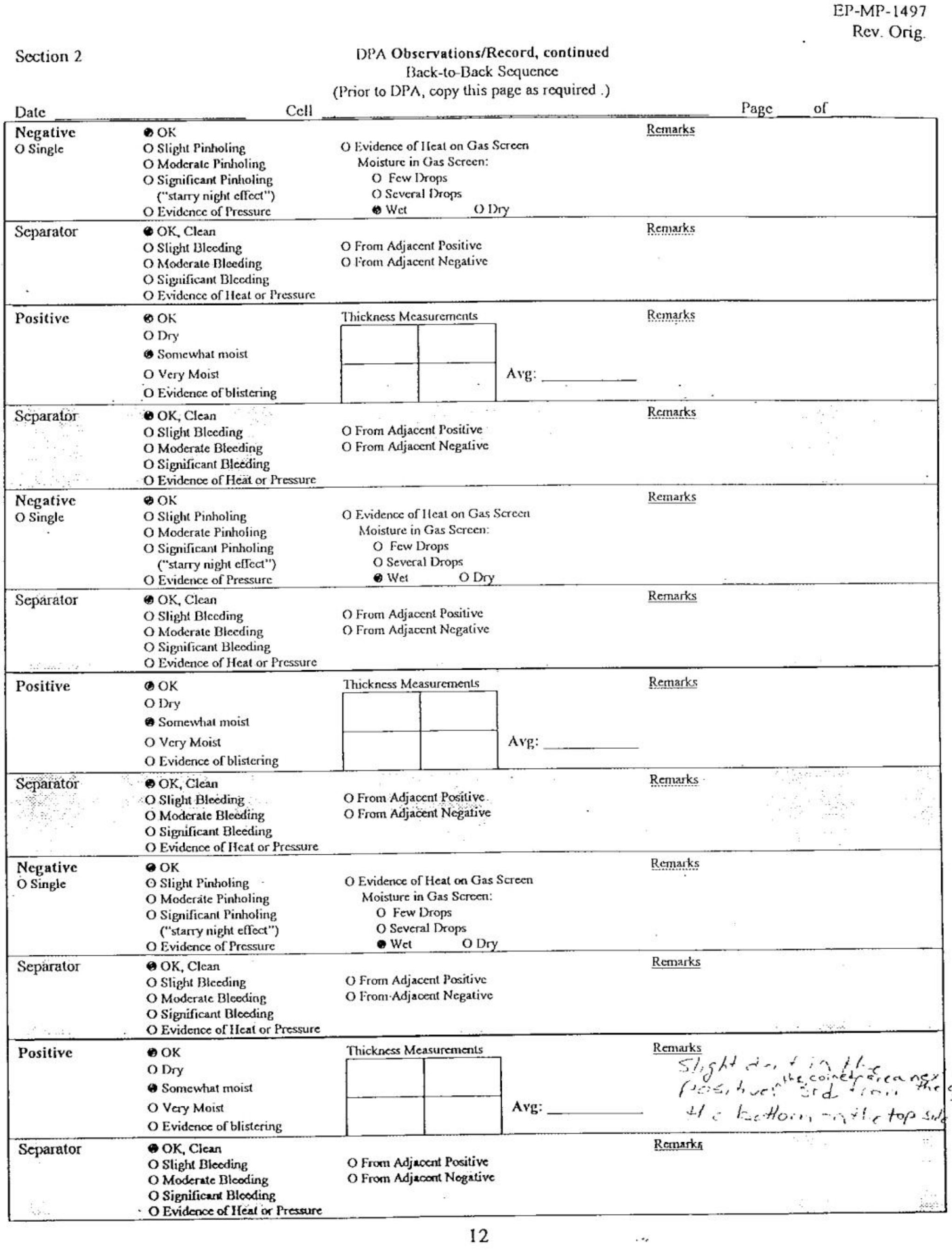
12



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Section 2

DPA Observations/Record, continued
Back-to-Back Sequence
(Prior to DPA, copy this page as required .)

Date ____________ Cell ____________ Page ____ of ____

Negative
○ Single
● OK
○ Slight Pinholing
○ Moderate Pinholing
○ Significant Pinholing ("starry night effect")
○ Evidence of Pressure
○ Evidence of Heat on Gas Screen
Moisture in Gas Screen:
○ Few Drops
○ Several Drops
● Wet ○ Dry
Remarks

Separator
● OK, Clean
○ Slight Bleeding
○ Moderate Bleeding
○ Significant Bleeding
○ Evidence of Heat or Pressure
○ From Adjacent Positive
○ From Adjacent Negative
Remarks

Positive
● OK
○ Dry
● Somewhat moist
○ Very Moist
○ Evidence of blistering
Thickness Measurements

Avg: ____________
Remarks

Separator
● OK, Clean
○ Slight Bleeding
○ Moderate Bleeding
○ Significant Bleeding
○ Evidence of Heat or Pressure
○ From Adjacent Positive
○ From Adjacent Negative
Remarks

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○ Single
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● Wet ○ Dry
Remarks

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○ Dry
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○ Very Moist
○ Evidence of blistering
Thickness Measurements

Avg: ____________
Remarks

Separator
● OK, Clean
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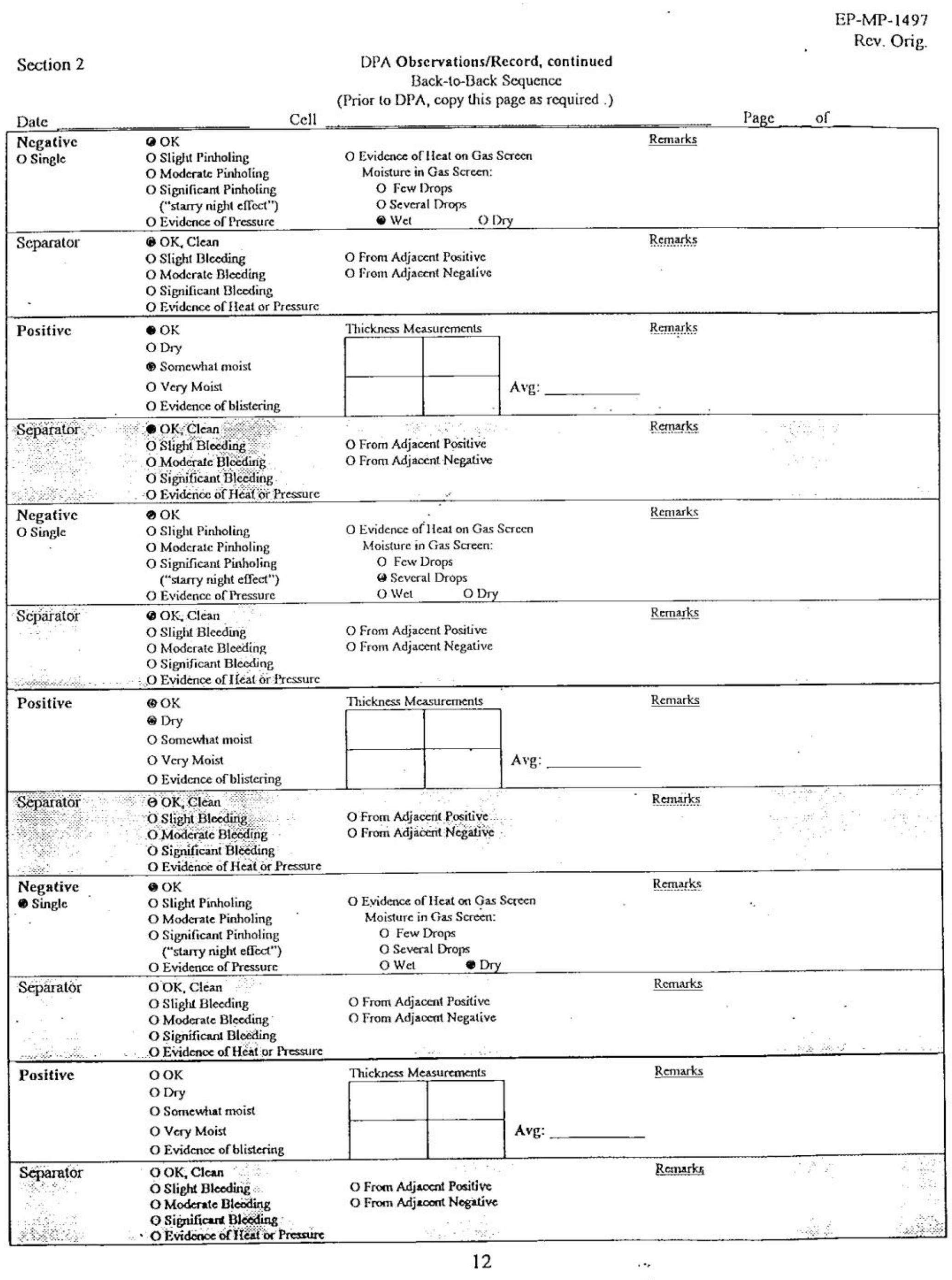
○ Slight Bleeding
○ Moderate Bleeding
○ Significant Bleeding
○ Evidence of Heat or Pressure
○ From Adjacent Positive
○ From Adjacent Negative
Remarks

Positive
● OK
○ Dry
● Somewhat moist
○ Very Moist
○ Evidence of blistering
Thickness Measurements

Avg: ____________
Remarks
Slight dent in the
positive the coined area next to end from the coi
the bottom on the top side

Separator
● OK, Clean
○ Slight Bleeding
○ Moderate Bleeding
○ Significant Bleeding
○ Evidence of Heat or Pressure
○ From Adjacent Positive
○ From Adjacent Negative
Remarks

12



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Section 2

DPA Observations/Record, continued
Back-to-Back Sequence
(Prior to DPA, copy this page as required .)

Date ______________ Cell ______________ Page ____ of ____

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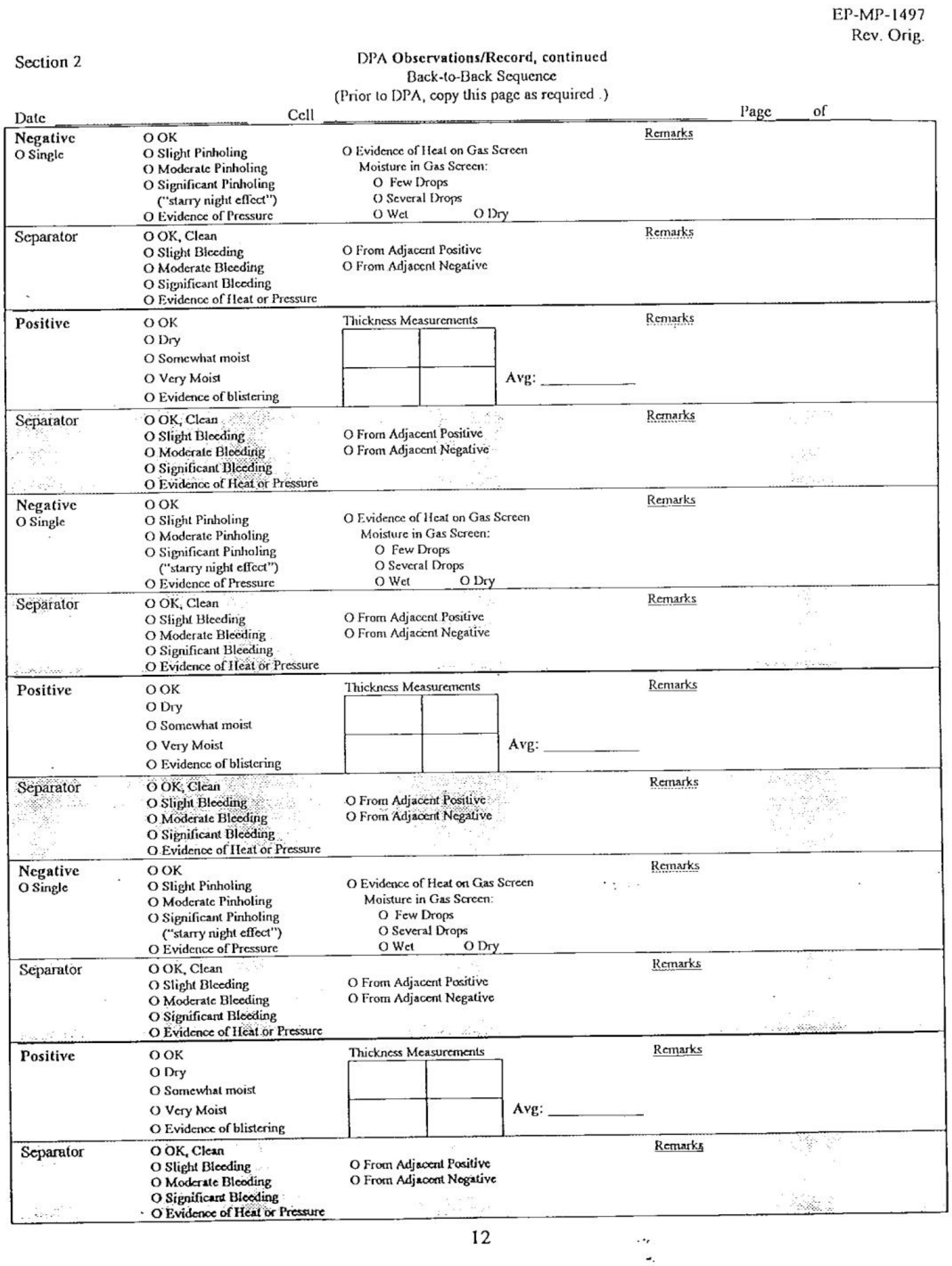
12



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Section 2

DPA **Observations/Record**, continued
Back-to-Back Sequence
(Prior to DPA, copy this page as required .)

Date ____________ Cell ____________ Page ____ of ____

Negative ○ Single	○ OK ○ Slight Pinholing ○ Moderate Pinholing ○ Significant Pinholing ("starry night effect") ○ Evidence of Pressure	○ Evidence of Heat on Gas Screen Moisture in Gas Screen: ○ Few Drops ○ Several Drops ○ Wet ○ Dry	Remarks
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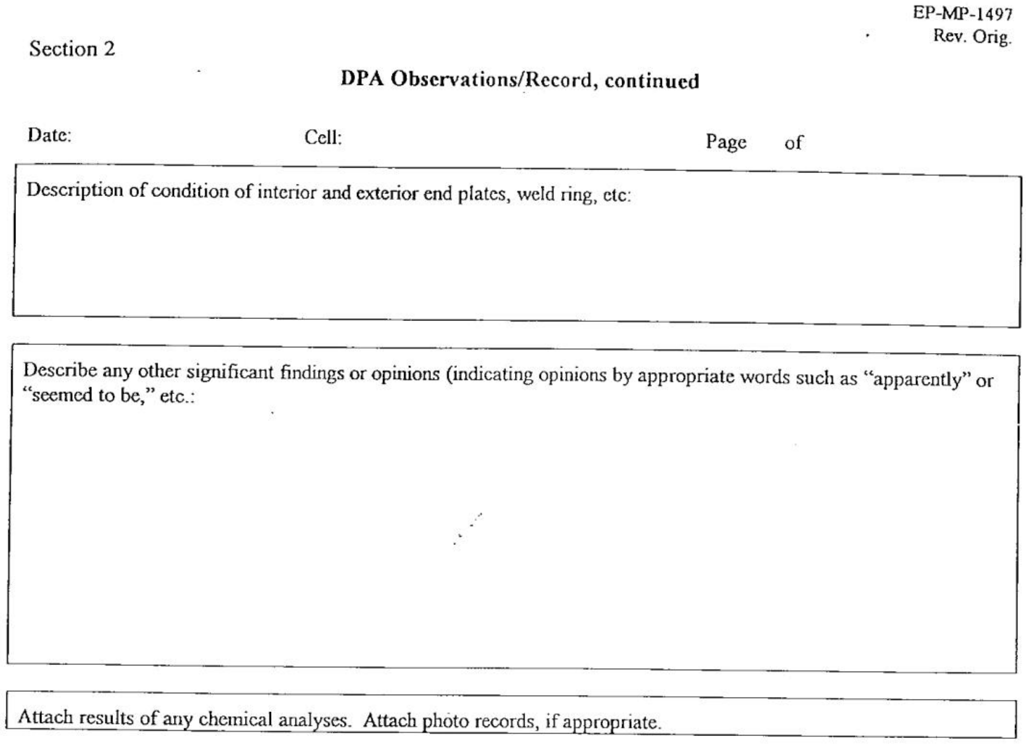

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Section 2

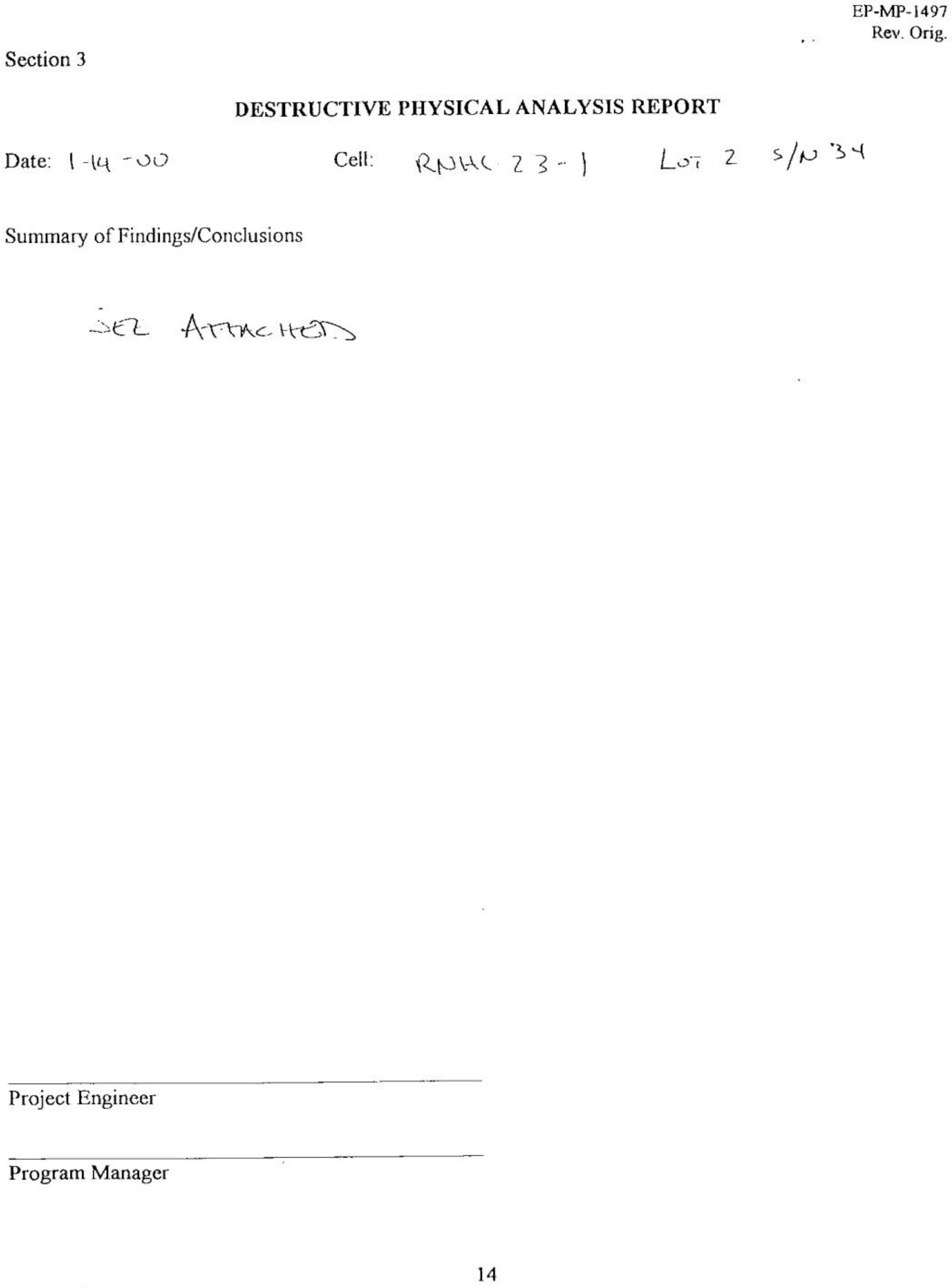
DPA Observations/Record, continued

Date:
Cell:
Page of

Description of condition of interior and exterior end plates, weld ring, etc:

Describe any other significant findings or opinions (indicating opinions by appropriate words such as "apparently" or "seemed to be," etc.:

Attach results of any chemical analyses. Attach photo records, if appropriate.



EP-MP-1497
Rev. Orig.

Section 3

DESTRUCTIVE PHYSICAL ANALYSIS REPORT

Date: 1-14-00 Cell: RNHC 23-1 LOT 2 S/N 34

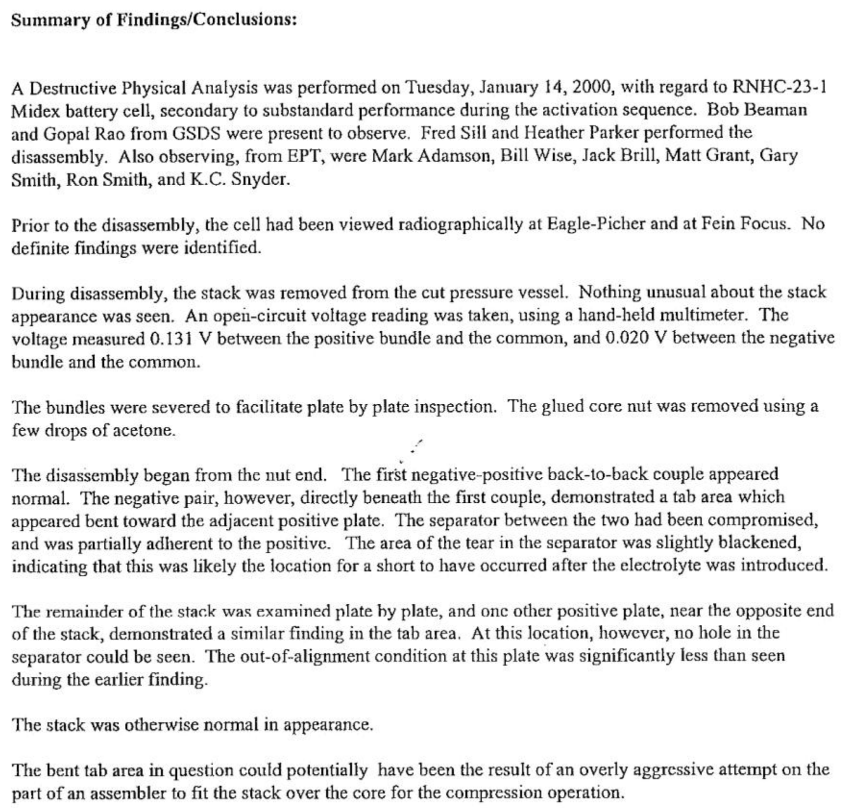
Summary of Findings/Conclusions

SEE ATTACHED

Project Engineer

Program Manager

14



Summary of Findings/Conclusions:

A Destructive Physical Analysis was performed on Tuesday, January 14, 2000, with regard to RNHC-23-1 Midex battery cell, secondary to substandard performance during the activation sequence. Bob Beaman and Gopal Rao from GSDS were present to observe. Fred Sill and Heather Parker performed the disassembly. Also observing, from EPT, were Mark Adamson, Bill Wise, Jack Brill, Matt Grant, Gary Smith, Ron Smith, and K.C. Snyder.

Prior to the disassembly, the cell had been viewed radiographically at Eagle-Picher and at Fein Focus. No definite findings were identified.

During disassembly, the stack was removed from the cut pressure vessel. Nothing unusual about the stack appearance was seen. An open-circuit voltage reading was taken, using a hand-held multimeter. The voltage measured 0.131 V between the positive bundle and the common, and 0.020 V between the negative bundle and the common.

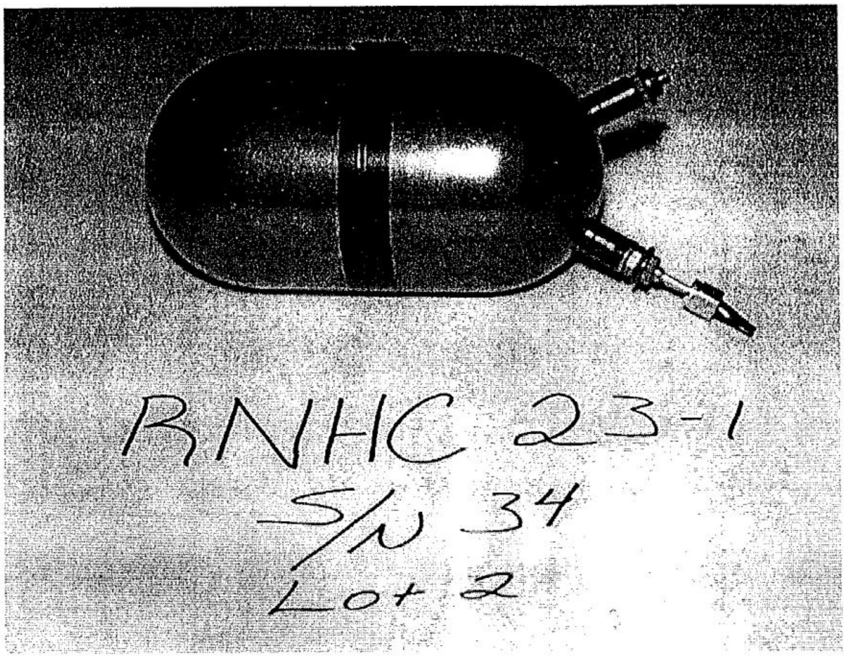
The bundles were severed to facilitate plate by plate inspection. The glued core nut was removed using a few drops of acetone.

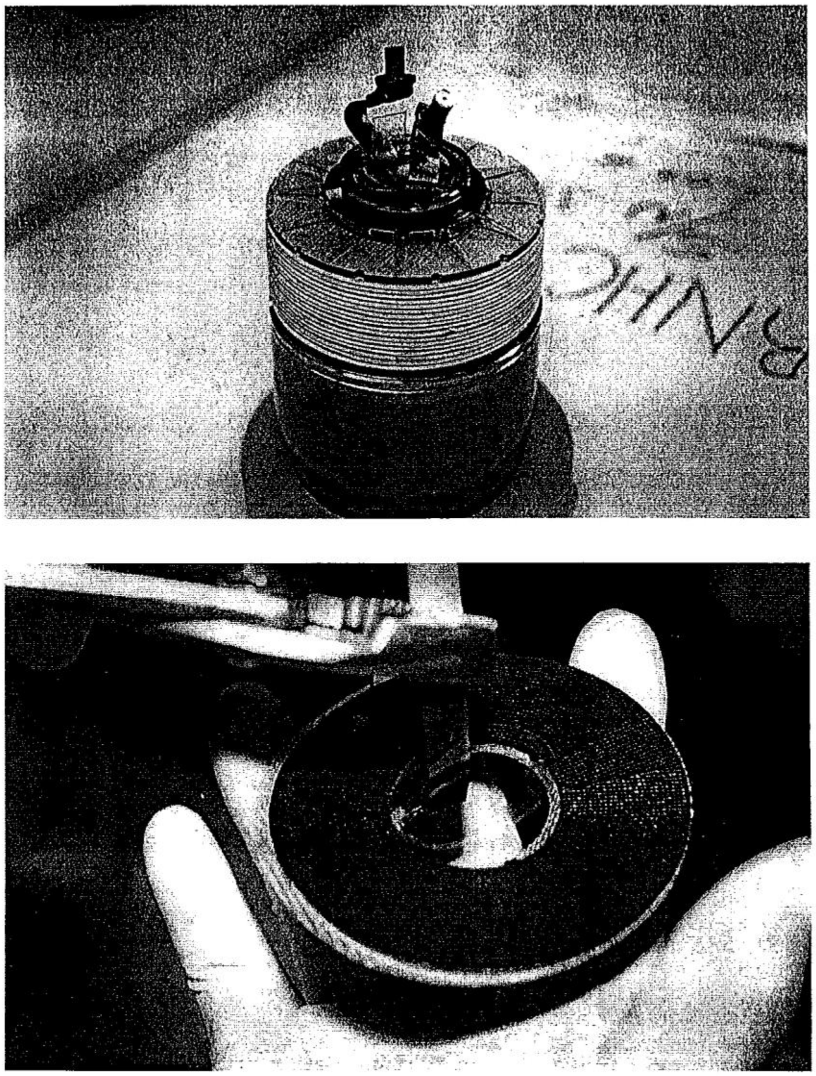
The disassembly began from the nut end. The first negative-positive back-to-back couple appeared normal. The negative pair, however, directly beneath the first couple, demonstrated a tab area which appeared bent toward the adjacent positive plate. The separator between the two had been compromised, and was partially adherent to the positive. The area of the tear in the separator was slightly blackened, indicating that this was likely the location for a short to have occurred after the electrolyte was introduced.

The remainder of the stack was examined plate by plate, and one other positive plate, near the opposite end of the stack, demonstrated a similar finding in the tab area. At this location, however, no hole in the separator could be seen. The out-of-alignment condition at this plate was significantly less than seen during the earlier finding.

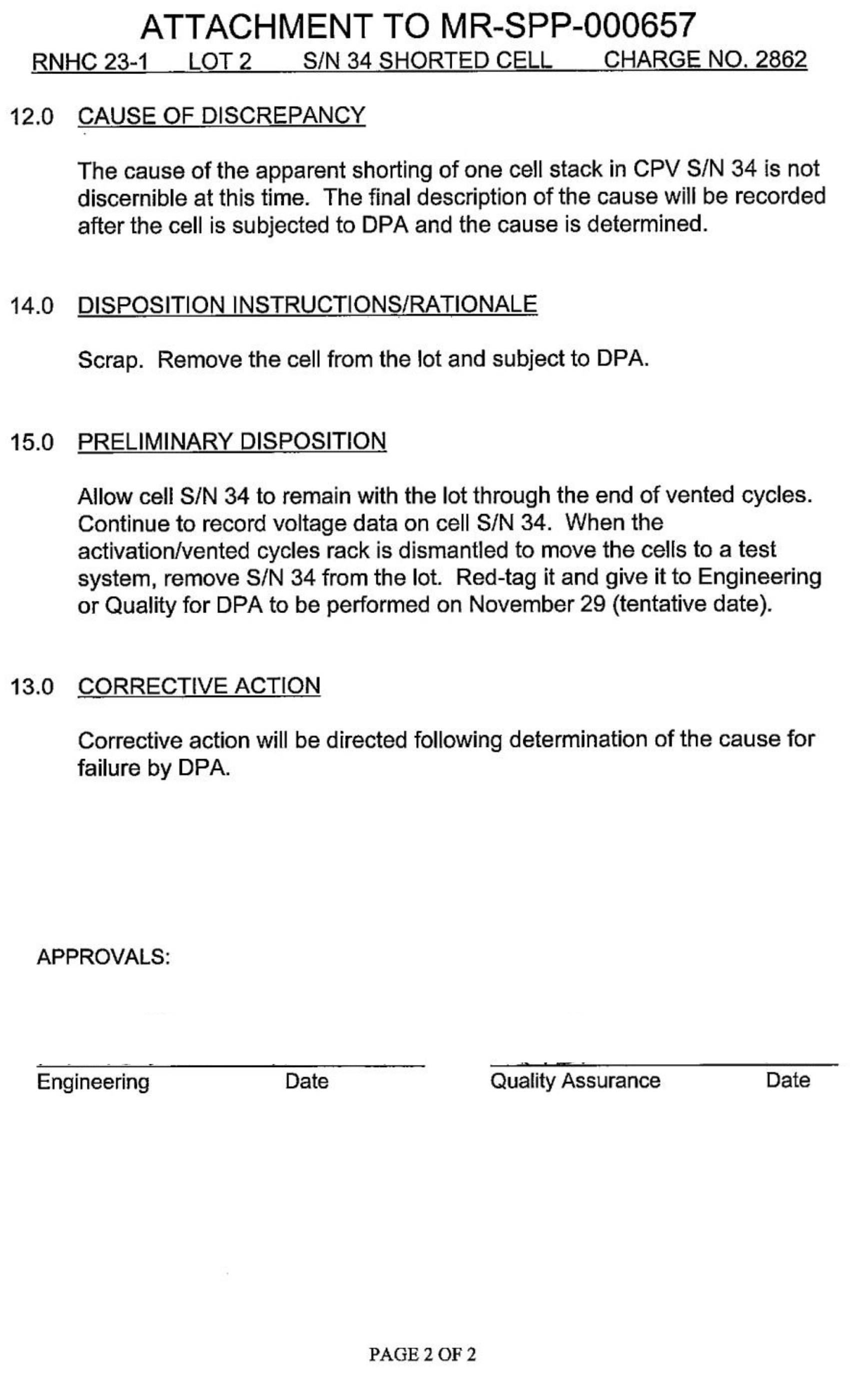
The stack was otherwise normal in appearance.

The bent tab area in question could potentially have been the result of an overly aggressive attempt on the part of an assembler to fit the stack over the core for the compression operation.


RNHC 23-1
S/N 34
Lot 2



Negative electrode tab area found misaligned during disassembly. Most likely resulted in the tear (hole) found in the separator, and allowed a shorting path to the adjacent positive electrode.



ATTACHMENT TO MR-SPP-000657

RNHC 23-1 LOT 2 S/N 34 SHORTED CELL CHARGE NO. 2862

12.0 CAUSE OF DISCREPANCY

The cause of the apparent shorting of one cell stack in CPV S/N 34 is not discernible at this time. The final description of the cause will be recorded after the cell is subjected to DPA and the cause is determined.

14.0 DISPOSITION INSTRUCTIONS/RATIONALE

Scrap. Remove the cell from the lot and subject to DPA.

15.0 PRELIMINARY DISPOSITION

Allow cell S/N 34 to remain with the lot through the end of vented cycles. Continue to record voltage data on cell S/N 34. When the activation/vented cycles rack is dismantled to move the cells to a test system, remove S/N 34 from the lot. Red-tag it and give it to Engineering or Quality for DPA to be performed on November 29 (tentative date).

13.0 CORRECTIVE ACTION

Corrective action will be directed following determination of the cause for failure by DPA.

APPROVALS:

Engineering Date Quality Assurance Date

PAGE 2 OF 2

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 01- 08 - 2010	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)* December 2009 - August 2010

4. TITLE AND SUBTITLE Wilkinson Microwave Anisotropy Probe (WMAP) Battery Operations Problem Resolution Team (PRT)	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Keys, Denney J.	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER 869021.05.07.05.06
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199	**8. PERFORMING ORGANIZATION REPORT NUMBER** L-19914 NESC-RP-10-00608
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	**10. SPONSOR/MONITOR'S ACRONYM(S)** NASA
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12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 05-Aircraft Design, Testing and Performance
Availability: NASA CASI (443) 757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The NASA Technical Discipline Fellow for Electrical Power, was requested to form a Problem Resolution Team (PRT) to help assess the health of the flight battery that is currently operating aboard NASA's Wilkinson Microwave Anisotropy Probe (WMAP) and provide recommendations for battery operations to mitigate the risk of impacting science operations for the rest of the mission. This report contains the outcome of the PRT's assessment.

15. SUBJECT TERMS

Battery operations; Common Pressure Vessel Nickel-Hydrogen; NASA Engineering and Safety Center; Problem resolution team; Wilkinson Microwave Anisotropy Probe

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
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					19b. TELEPHONE NUMBER ***(Include area code)***
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