



1996 NASA AEROSPACE BATTERY WORKSHOP

**THE IN-ORBIT BATTERY RECONDITIONING
EXPERIENCE ON BOARD THE
ORION 1 SPACECRAFT**

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The Orion 1 spacecraft is a three-axis stabilized geostationary earth orbiting commercial communications satellite which was launched on November 29, 1994 aboard an Atlas II launch vehicle. The power subsystem is a dual bus, dual battery semi-regulated system with one 78 Ampere-hour nickel-hydrogen battery per bus. The batteries were built and tested by Eagle Picher Industries, Inc., of Joplin, MO and were integrated into the spacecraft by its manufacturer, Matra Marconi Space UK Ltd.

This paper presents the results obtained during the first four in-orbit reconditioning cycles and compares the battery performance to ground test data. In addition, the on-station battery management strategy and implementation constraints are described. Battery performance has been nominal throughout each reconditioning cycle and subsequent eclipse season.



Overview

- Battery Specifications
- Power Requirements
- Cell and Battery Characteristics
- Power Subsystem Block Diagram
- Power Subsystem Capabilities
- Objectives for Reconditioning
- Reconditioning Procedure
- Data
- Conclusion

This paper will discuss the battery specifications and power requirements that Orion Satellite Corporation presented to Matra Marconi Space for the Orion 1 satellite design. The selected cell and battery characteristics which satisfy the requirements will be identified. A brief description of the Eurostar 2000 power subsystem and its capabilities will be presented.

Following the objectives for reconditioning and procedure outline, the in-orbit results will be displayed and compared to ground test data. Finally, the achieved objectives will conclude the presentation.



Orion 1 Battery Specifications (1)

- Capable of supplying power to support launch, transfer orbit, and on-station eclipse operations (worst case: one failed cell per battery)
- Maximum depth of discharge < 70% (no cell failure) of nameplate capacity, DOD < 75% (one failed cell)
- Adequate charging system to recharge between eclipses
- Automatic end of charge control based on charge/discharge ratios or battery voltage/temperature limits
- Ability to override and/or inhibit the automatic end of charge control by ground command

The specifications that Orion Satellite Corporation (OSC) presented to Matra Marconi Space (MMS) for the Orion 1 satellite design were basically industry standard. The specifications were written to ensure that the power subsystem and all appropriate units of the subsystem were designed, manufactured, and demonstrated to meet the worst case power requirements during the various phases of the spacecraft mission over the entire designed orbital life-time of 10.5 years.



Orion 1 Battery Specifications (2)

- Sufficient telemetry to assess battery performance (voltage, current, temperature, pressure, etc.), including individual cell voltages
- Each battery shall be equipped with battery cell by-pass diodes for charge/discharge protection
- Capability to reconditioning each battery independently
- High and low discharge rates shall be selectable by ground
- No single point failure of the Power Subsystem shall inhibit the ability to charge and/or recondition either battery

In addition, the specifications were written to ensure that the battery performance can be monitored and protected automatically or by ground control. These requirements allow autonomous operation as well as operator intervention, if necessary, in the event of a failure. The power subsystem was designed such that no single point failure would affect the normal operation of the spacecraft; thus, all requirements of the Orion 1 spacecraft technical specification were satisfied.



Orion 1 Power Requirements

- Based on power estimates from unit manufactures
- The 75% DOD limit yielded a 78 Ah capacity battery
- Selected Eagle-Picher Industries, Inc. Ni-H₂ RNH-78 cell

| | Solstice (Watts) | Equinox (Watts) | Eclipse (Watts) |
|----------|---------------------|--------------------|--------------------|
| Payload | 2465 | 2465 | 2500 |
| Platform | 199 | 200 | 182 |
| Thermal | 230 | 393 | 142 |
| Charging | 66 | 336 | 0 |
| Total | 2960 | 3394 | 2824 |
| Margin | 460 | 360 | >25% SOC |

The total power budget was derived from the power requirements estimated by the unit manufactures. The batteries must support 2824W of power for the eclipse season. An average battery terminal voltage of 31.2 V (27 cells at 1.2 V per cell, with 1 failed cell) and a 700 mV drop across the battery diodes were used to calculate the minimum voltage. In addition, a maximum 5% imbalance between the two buses was also factored in the battery eclipse analysis.

$$2842 \text{ W} \div 2 \times 1.05 \div (31.2 - 0.7) \text{ V} \times 1.2 \text{ hr} = 58.3 \text{ Ah}$$

Therefore to meet the 75% depth of discharge specification, a battery with a capacity of 78 Ah was selected for this mission.



Orion 1 Cell Characteristics

- Manufacturer: Eagle-Picher Industries, Inc.
- Type: Mantech design,
Slurry-asbestos dual stack,
Axial terminals,
Hydrogen pre-charge
- Capacity (10°C): 78 Ampere-hours
- Dimensions: Length = 12.6", Diameter = 3.51"
- Mass: 1.87 ± 0.06 kg
- Heritage: Telecom 2 and Hispasat

The EPI (Eagle-Picher Industries, Inc.) nickel-hydrogen RNH-78 cell was an established design with in-orbit heritage on MMS' (Matra Marconi Space) Telecom 2 and Hispasat programs. The standard EPI "Mantech" design is a dual back-to-back stack of pineapple sliced plates with axial terminals. The electrode stack geometry provides optimal thermal characteristics for heat rejection capability.



Orion 1 Battery Characteristics

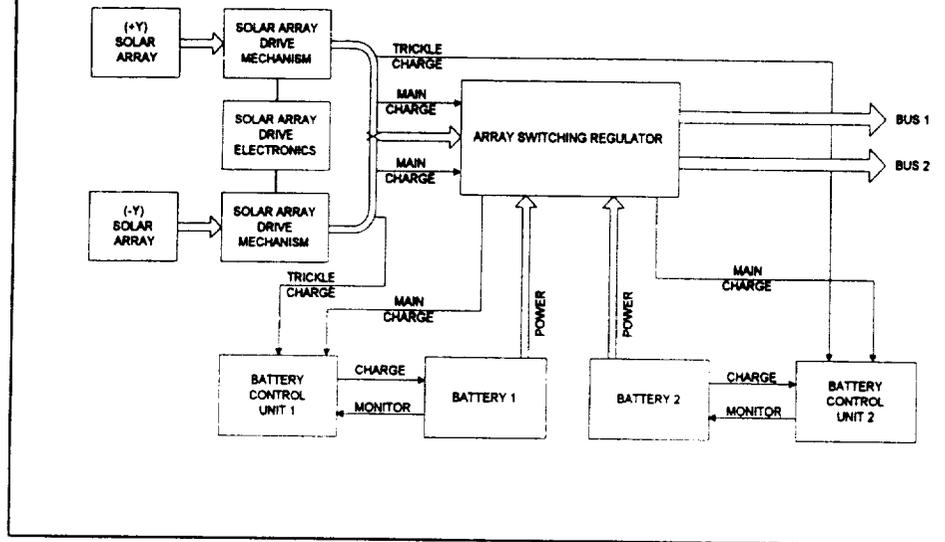
- Manufacturer: Eagle-Picher Industries, Inc.
- Type: 27 series connected 78 Ah cells,
By-pass diode network
4 heater circuits,
Voltage, current, temperature, and
pressure sensors
Individual cell voltage monitoring
- Dimensions: Length=39.8", Width=18.8", Height=12.9"
- Mass: 67.4 kg
- Heritage: Telecom 2 and Hispasat

One battery pack consists of 3 rows of 9 cells with all 27 connected in series. Each cell has a by-pass diode network for failure protection. The network consists of 3 diodes in series for by-passing the cell during charge and 1 diode in parallel for the discharge case. In addition, each battery has individual cell voltage telemetry which is sequentially scanned approximately once a minute (i.e., every other format).

Each battery has one terminal voltage, one pressure, two current, and three temperature sensors for telemetry monitoring. Two of the thermistors are located on the top (i.e., the dome of the cell that points towards the interior of the spacecraft) of two separate cells. The third thermistor is located on the bottom (i.e., the dome near the radiator panel) of one of the two previous cells. This thermistor configuration provides a cell-to-cell gradient as well as a cell temperature delta to calculate radiator panel efficiency.



Orion 1 Power Subsystem Block Diagram



The power subsystem (PSS) provides electrical power to the spacecraft subsystems and payload for all phases of the mission. The power supply is regulated in sunlight and unregulated in eclipse. A functional block diagram of the PSS is shown above. The PSS may be described as a twin bus, twin battery, semi-regulated system. The power is generated from silicon n-on-p solar cells which are mounted on two solar array wings, each wing consisting of four panels. Power is transferred to the array switch regulator (ASR) by the solar array drive mechanism slip-rings. The wings are independently rotated about the pitch axis of the spacecraft to maintain sun pointing.

During periods when solar power is not available, the satellite is powered from energy stored in two nickel-hydrogen batteries. The batteries are recharged in sunlight from dedicated solar array sections. These sections provide a constant current source for charging. Trickle chargers are also available to assist main charge; however, the chargers are primarily used to maintain the battery state of charge. There are four such chargers, two in each battery control interface unit (BCIU).

Each battery provides a supply voltage of nominally 27 to 42 V at the PSS output interface. Battery 1 supports main bus 1 and battery 2 is dedicated to main bus 2.



Orion 1 Power Subsystem Capabilities

- Solar array main charge sections to either battery (C/17)
- Flexibility to charge with both main charge sections (C/9)
- Trickle chargers can be set to variable rates (0 to C/65)
- All 4 trickle chargers can be configured to assist main charge
- Automatic EOC, EOD, over-temperature, and under-voltage protection provided
- Independent battery reconditioning, discharge at high or low rate (C/39 or C/105)

The MMS Eurostar 2000 power subsystem provides various capabilities and configurations for flexible operations. The numerous charge rates which can be selected by ground control combined with the autonomous protection functions allow the user to optimize the power subsystem. However, minimizing the configuration changes reduces the number of variables in the battery capacity analysis and produces comparable results.



Objectives for Reconditioning

- To provide a health check of the battery
- To measure cell performance and characteristics
- To provide a bi-annual assessment of the “usable” capacity
- To help decrease or remove the capacity “fade” due to pre-launch storage
- To increase capacity and maintain the battery at the highest level of performance

Reconditioning provides an opportunity to assess and status the health of the each battery twice a year. The procedure also allows the operator to trend the performance of the cells and identify any end of life concerns regarding power margin. It should be noted that the battery capacity “fade” due to pre-launch storage may be reduced or even eliminated by in-orbit reconditioning. However, reconditioning allows one to identify and track the useful capacity of each battery and maintain the batteries at the highest performance level.



Reconditioning Procedure (1)

- Initial discharge
 - Trickle charger switched off (1 per battery)
 - Battery connected to primary and secondary loads of 36 ohms each
 - Discharge current of approximately 2.0 Amps
 - Discharge until minimum cell voltage reaches 1.05 Volts

- Reduced rate discharge
 - Secondary load disconnected
 - Discharge current of approximately 1.0 Amps
 - Discharge until minimum cell voltage reaches 0.5 Volts

In order to maintain the highest level of performance, each battery is sequentially reconditioned. One battery remains fully charge to optimize satellite safety. The reconditioning battery is connect to both the primary and secondary loads and discharged until the minimum cell voltage reaches 1.05 V. After disconnecting the secondary load, the battery is further discharged until the minimum cell voltage reaches 0.5 V. The reconditioning loads are located on the battery radiator panels.



Reconditioning Procedure (2)

- Recharge
 - K-factor (C/D ratio) set to 1.25
 - Charge via main charge (approx. 4.5A, C/17) until 700 psi is reached
 - Update K-factor to 1.15
 - Set Amperehour meter to derived parameter value (P/T)
 - Charge via main charge until Amperehour meter reaches 82 Ahrs
 - Monitor battery voltage < EOC voltage threshold (42.45 V)
 - Monitor battery temperature profile (rate of increase < 4°C/hour)
 - The over-temperature threshold is 26 °C
- End of charge
 - Trickle charger switched on
 - Set trickle charge rate to 0.48A (C/163)

The battery is recharged to 700 psi with a C/D ratio of 1.25. At 700 psi, the on board integrated coulometer is updated to the ground derived amperehour value. The derived parameter value is based on the actual battery pressure and temperature from telemetry with correction factors determined from ground tests. Following the amperehour update, the battery is recharged with a C/D ratio of 1.15 to 82 Ahrs. Charge is terminated manually. The 82 Ahrs is the maximum battery capacity value set by ground command. This value was also determined during ground testing. While approaching end of charge, the battery voltage and temperature are closely monitored to ensure that the hardware logic threshold for EOC is not violated. In addition, the exothermic characteristics of the Ni-H₂ battery are monitored for over temperatures. Finally, the battery is placed on trickle charge using the nominal on-station electronic trickle charger configuration and rate. Once the exothermic characteristics taper off, the trickle charger provides the remaining charge to the battery in order to approach 100% state of charge.



Orion 1 Reconditioning Data (1)

- Four cycles completed with nominal results
- Capacity increase has stabilized

| | | BATTERY 1 (N) | | | | BATTERY 2 (S) | | | |
|-----------------|-----------|---------------|-------------|-------------|-------------|---------------|-------------|-------------|-------------|
| | | #1 WS 95 | #2 SS 95 | #3 WS 96 | #4 SS 96 | #1 WS 95 | #2 SS 95 | #3 WS 96 | #4 SS 96 |
| Start | | 12/25/94 | 7/17/95 | 2/12/96 | 7/29/96 | 1/6/95 | 7/31/95 | 1/29/96 | 8/12/96 |
| End | | 12/28/94 | 7/21/95 | 2/15/96 | 8/2/96 | 1/10/95 | 8/4/95 | 2/2/96 | 8/16/96 |
| Duration (hr) | High Rate | 39.52 | 45.23 | 46.15 | 46.32 | 39.44 | 45.51 | 46.39 | 46.55 |
| | Low Rate | 52.56 | 57.12 | 59.10 | 58.01 | 55.57 | 58.34 | 59.08 | 58.54 |
| | Charge | 19.15 | 26.09 | 24.41 | 25.36 | 19.48 | 26.21 | 25.41 | 26.18 |
| Discharge (Ahr) | High Rate | 81.59 | 91.95 | 96.25 | 96.95 | 83.45 | 93.40 | 97.24 | 97.60 |
| | Low Rate | 11.90 | 9.76 | 11.00 | 9.55 | 12.89 | 10.67 | 10.03 | 9.51 |
| | Total | 93.49 | 101.71 | 107.25 | 106.50 | 96.34 | 104.07 | 107.27 | 107.11 |
| Stop Discharge | High Rate | Cell 10 | Cell 10 | Cell 10 | Cell 10 | Cell 1 | Cell 1 | Cell 1 | Cell 2 |
| | Low Rate | Cell 10 | Cell 10 | Cell 10 | Cell 10 | Cell 5 | Cell 5 | Cell 5 | Cell 16 |
| | Charge | 82 Ahr | 82 Ahr | 82 Ahr | 82 Ahr | 82 Ahr | 82 Ahr | 82 Ahr | 82 Ahr |
| Pressure (psi) | High Rate | 242 | 230 | 230 | 219 | 200 | 188 | 188 | 188 |
| | Low Rate | 150 | 150 | 150 | 150 | 100 | 100 | 100 | 112 |
| | Charge | 956 | 967 | 978 | 967 | 923 | 969 | 969 | 992 |
| Min Voltage (V) | High Rate | 33.42 | 33.13 | 33.13 | 32.93 | 33.59 | 32.73 | 32.33 | 31.52 |
| | Low Rate | 24.74 | 23.85 | 24.09 | 24.30 | 23.46 | 23.29 | 23.29 | 22.93 |
| | Charge | 42.3 | 42.12 | 41.76 | 42.12 | 42.30 | 42.12 | 41.96 | 41.96 |
| Charge (Ahr) | Total | 106.50 | 111.04 | 112.67 | 111.15 | 112.30 | 115.18 | 115.87 | 116.31 |

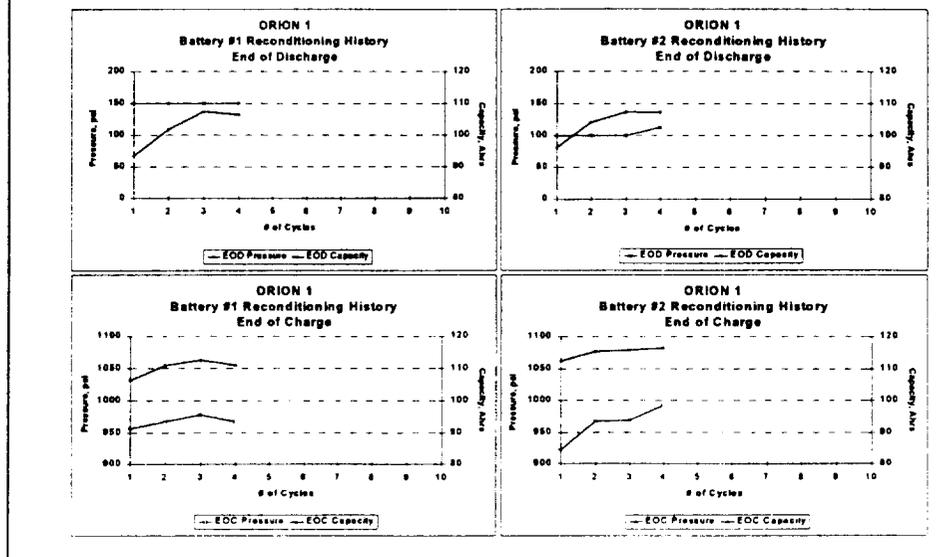
The first reconditioning cycle was performed by MMS prior to acceptance. Due to timing constraints, the procedure used during the first cycle was modified to expedite the activities. The subsequent cycles have been performed by Orion Satellite Corporation with consistent procedures. By the fourth cycle, both batteries have exhibited an increase in end of discharge (EOD) capacity of approximately 10-12% compared to the first reconditioning cycle. The increase was expected as the capacity "fade" due to pre-launch storage decreases during the first few cycles.

It should be noted that cell 10 on battery 1 has consistently been the driving cell for terminating discharge. Cell 10 also demonstrated weaker characteristics compared with the other battery 1 cells during ground testing. The battery 2 cells, on the other hand, are more closely matched. The discharge termination cell on battery 2 has varied.

The return capacities have increased by 3-5% compared to the first cycle. The minimum battery voltages and pressures have been consistent throughout the first four cycles. However, due to the location of the batteries and the thermal influence of solar input, it is believed that a season to season comparison provides an improved assessment of the results.



Orion 1 Reconditioning Data (2)

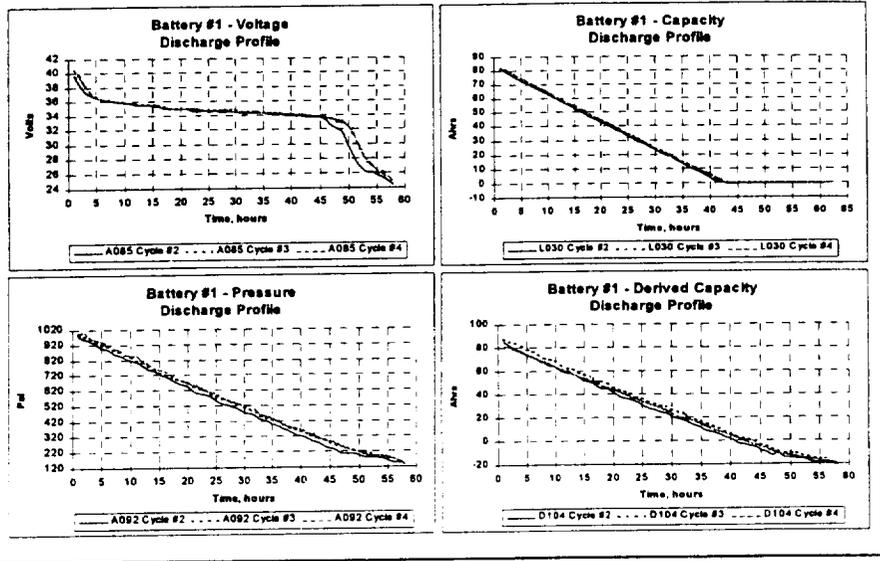


The end of discharge capacity increase provides evidence that the capacity “fade” due to pre-launch storage has decreased during the first few cycles. The “knee” shown in the EOD curves indicates that the capacity increase may have stabilized for both batteries. In addition, the end of charge capacities have increased by 3-5% from the first cycle and appear to have also stabilized. The EOD and EOC pressures have remained relatively constant ($\pm 1-2$ telemetry bits, where 1 bit = 12 psi) throughout the first four cycles.

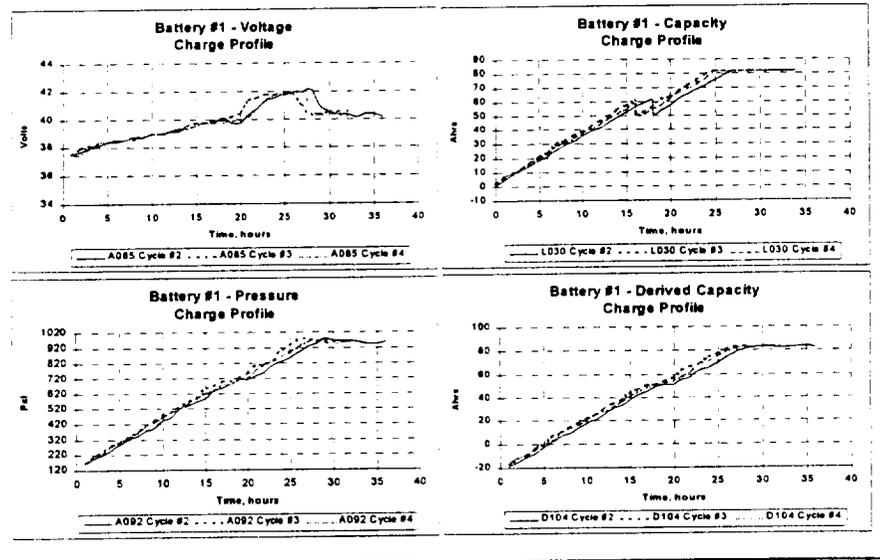
The following graphs illustrate and compare the actual in-orbit discharge and charge cycles performed by Orion Satellite Corporation. Both batteries have exhibited consistent results.



Orion 1 Reconditioning Data (3)

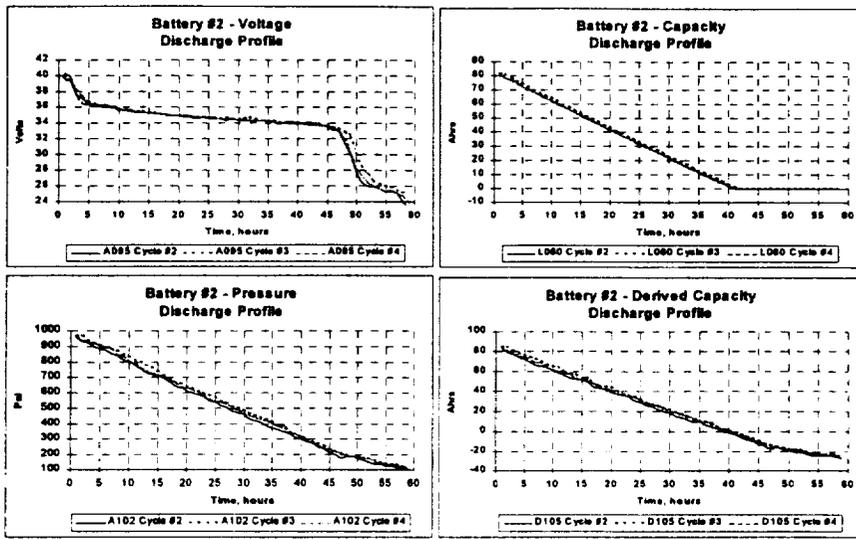


Orion 1 Reconditioning Data (4)

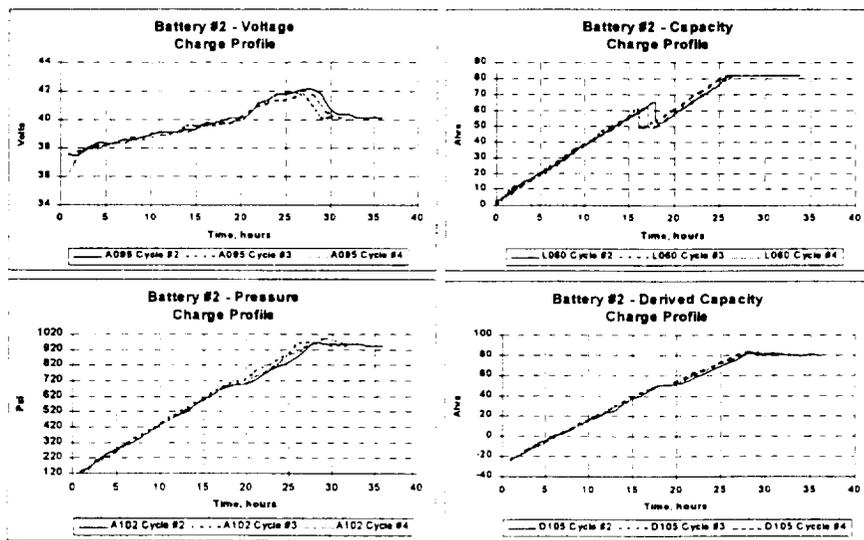


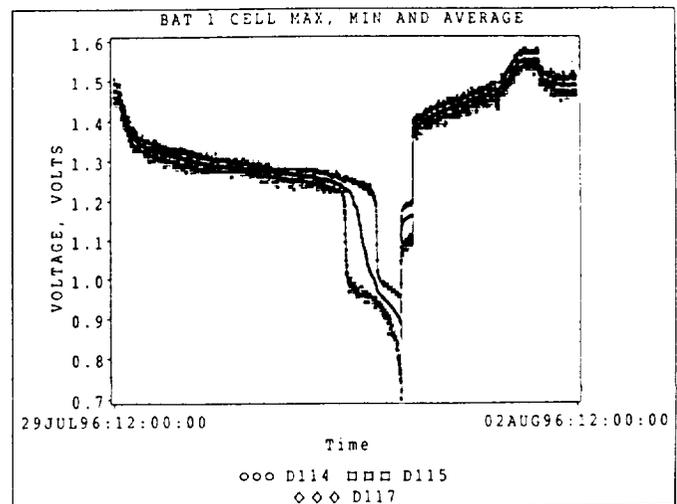
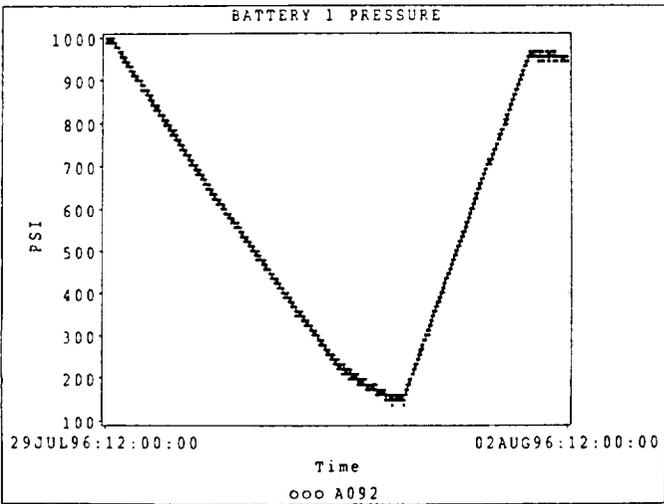
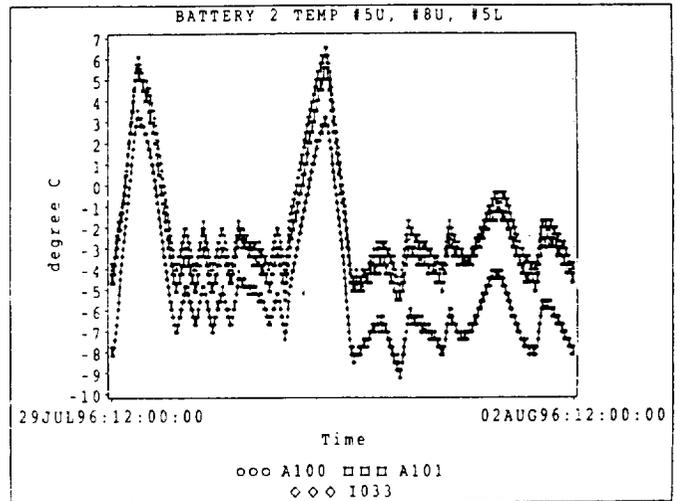
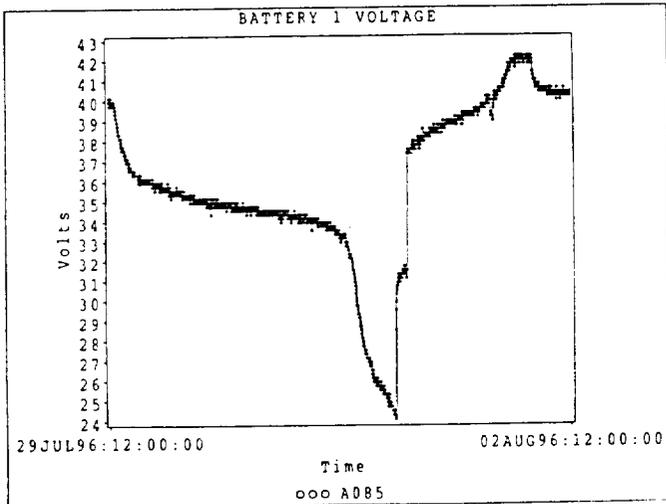
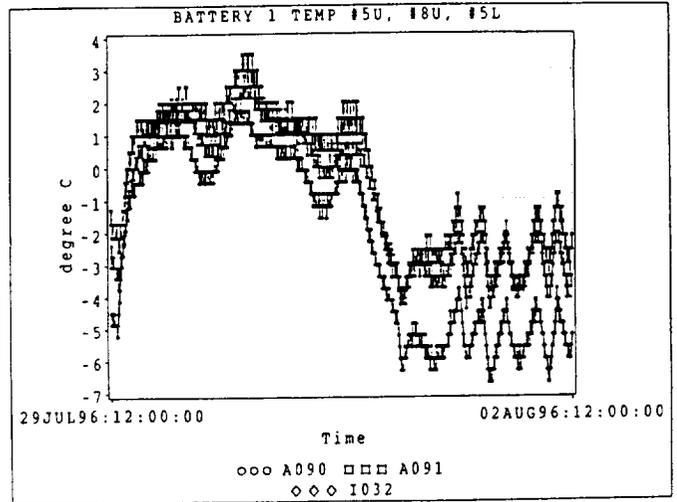
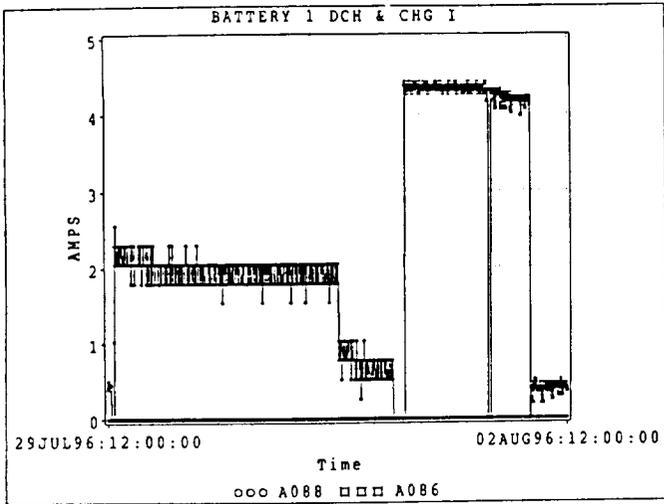


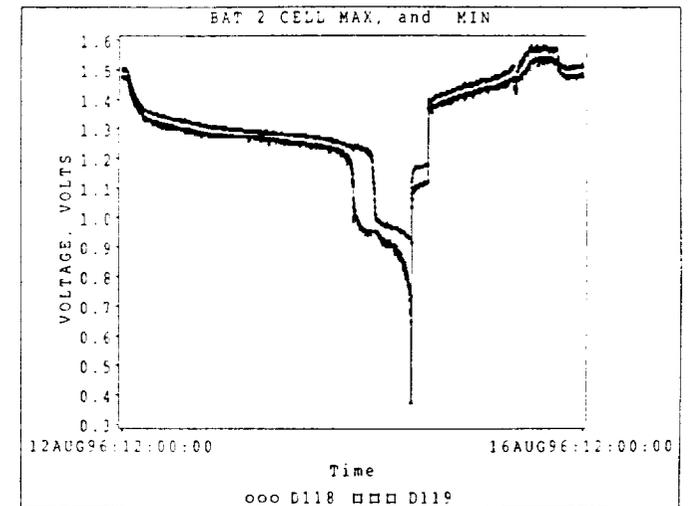
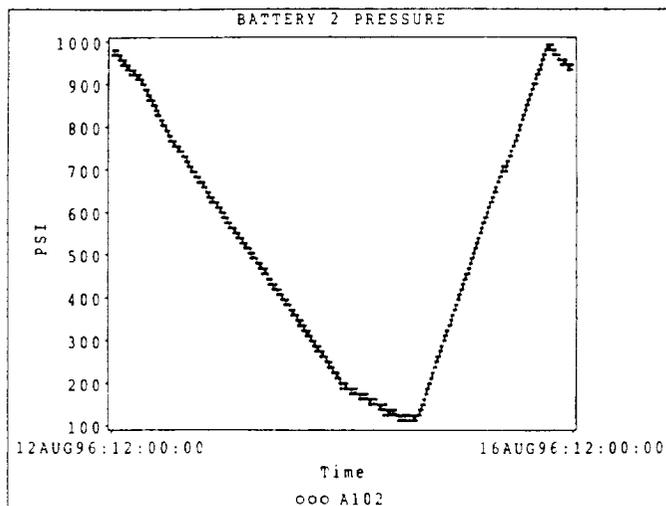
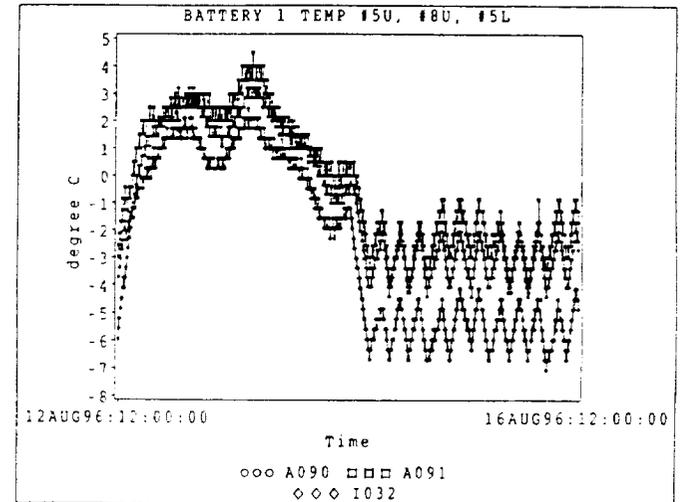
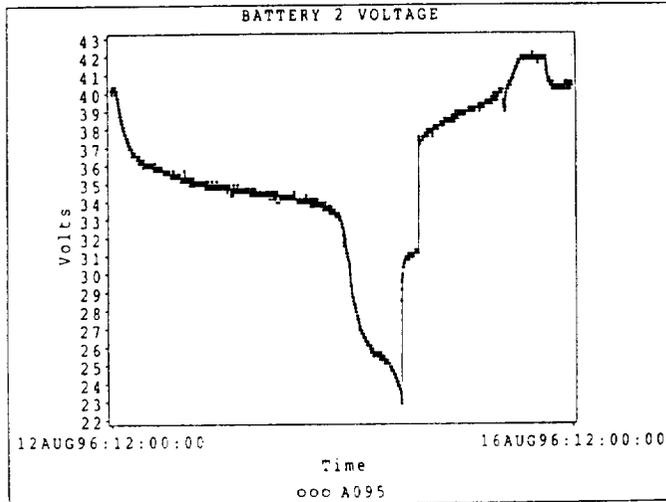
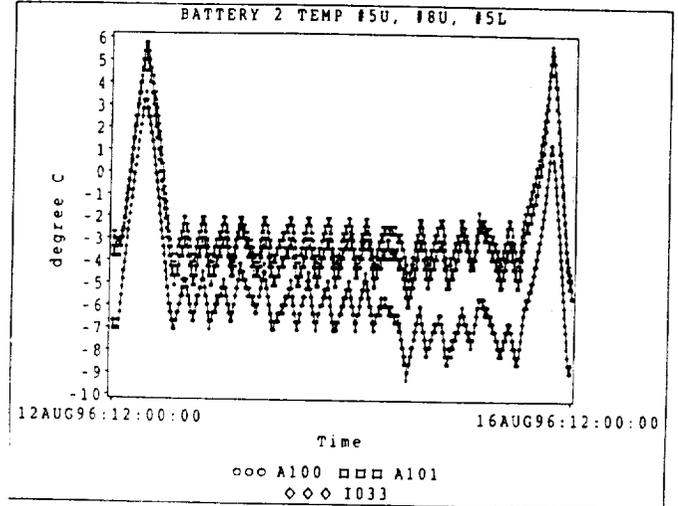
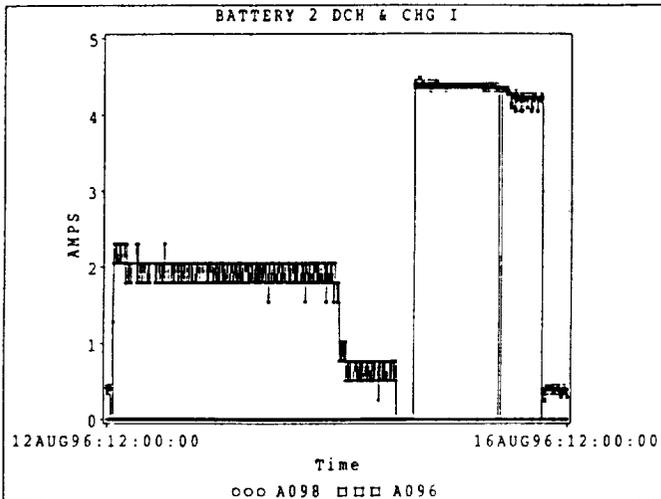
Orion 1 Reconditioning Data (5)



Orion 1 Reconditioning Data (6)









Orion 1 Reconditioning Data (7)

- Reconditioning was performed by MMS during spacecraft solar simulation (SST) and simmer (TVT) tests
- In-orbit data is consistent with ground test results

| | | BATTERY 1 (N) | | BATTERY 2 (S) | |
|-----------------|-----------|---------------|---------|---------------|---------|
| | | SST | TVT | SST | TVT |
| Start | | 4/27/94 | 8/11/94 | 4/27/94 | 8/11/94 |
| End | | 5/1/94 | 8/16/94 | 5/1/94 | 8/16/94 |
| Discharge (Ahr) | High Rate | 95.1 | 93.1 | 94.9 | 92.4 |
| | Low Rate | 12.5 | 11.9 | 12.9 | 12.6 |
| | Total | 107.6 | 105.0 | 107.8 | 105.0 |

During spacecraft ground tests, reconditioning was performed on each battery by Matra Marconi Space. The results are shown above. These results have been compared to the in-orbit data and found to be consistent. The discharge and charge profiles have also been compared to the in-orbit profiles and found to be satisfactory.



Conclusion

- Four cycles completed with nominal results
- In-orbit data is consistent with ground test results
- “Usable” capacity has been assessed
- Capacity increase appears to have stabilized
- Battery performance has been satisfactory during subsequent eclipse seasons

The Orion 1 satellite has satisfactorily completed the first four in-orbit battery reconditioning cycles. Both batteries have exhibited consistent and nominal results compared to ground test data. Battery reconditioning has provided a bi-annual assessment of the “usable” capacity, established an in-orbit performance baseline, and furnished an opportunity to trend the current performance which may identify any end of life power margin concerns. After two years on-station, the Orion 1 batteries have performed nominally with no present concerns.