JOURNAL OF PROPULSION AND POWER
Vol. 12, No. 5, September–October 1996

# Space-Station Nickel–Hydrogen Battery Orbital Replacement Unit Test

Fred Cohen*
*Rockwell International Corporation, Canoga Park, California 91306-7922*
and
Penni J. Dalton†
*NASA Lewis Research Center, Cleveland, Ohio 44136*

**The International Space Station electrical power system utilizes nickel–hydrogen ($Ni-H_2$) batteries as part of its power system to store electrical energy. The batteries are charged during insolation and discharged during eclipse. The batteries are designed to operate at a 35% depth of discharge maximum during normal operation. Thirty-eight individual pressure vessel $Ni-H_2$ battery cells are series-connected and packaged in an orbit replacement unit (ORU). Two ORUs are series connected, a total of 76 cells, to form one battery. The International Space Station will be the first application for low Earth orbit cycling of this quantity of series connected cells. The Space Station Photovoltaic Electronics Team, consisting of NASA and Rocketdyne personnel, began a unique test program at the Power Systems Facility at the NASA Lewis Research Center. The test plan was created to evaluate near- and long-term performance as a battery as well as charge management characteristics. The testing would also validate the ORU configuration including the ORU box and thermal interface design. This article describes the test program and the results of the 3000 LEO cycles on a Space Station engineering model battery.**

## Introduction

A BATTERY consisting of two series connected engineering model (EM) orbital replacement units (ORUs) was tested in the Power Systems Facility (PSF) at the NASA Lewis Research Center.

The test configuration utilizes a Space Station-type finned thermal interface and is combined with a closed circuit chilled water cooling system. This is done to simulate the Space Station thermal control system (TCS) configuration. The ORUs and thermal interfaces are contained in a dual compartment environmentally controlled chamber that is continuously nitrogen purged and maintained at the nominal Space Station operating temperature of 5°C (41°F). The battery is electrically cycled and monitored by an automated charge/discharge controller and data acquisition system. The orbit consists of a 35% depth of discharge (DOD) (maximum) peaking low Earth orbit (LEO) cycle that is based on the Space Station power system requirements from the Rocketdyne Battery Subassembly ORU Specification (see Table 1).

The two engineering model battery ORUs in this test were procured through the Space Station prime contractor and used off the shelf Gates Aerospace $Ni-H_2$ battery cells (GAB, now SAFT). The cells are nameplate 89 A-h capacity, recirculating design and contain 31% aqueous solution of potassium-hydroxide (KOH) electrolyte. The battery subassembly ORU nameplate capacity rating is 81 A-h.

Currently, there is no life or performance database for LEO cycling of more than 22 $Ni-H_2$ cells in series.[1] Life is an important consideration; hence, a low-stress charge profile was developed that would minimize heat generation at higher states of charge where efficiency tends to be reduced. The battery design requirement for life is 5 years consisting of 29,200 35% LEO cycles. Since these ORUs are the first of their kind with a unique finned thermal interface, testing would also serve to prove the design concept and validate the battery ORU for use on the International Space Station.

Independent LEO nonpeaking (see Table 1) testing was performed on ORUs to evaluate their compatibility. ORU EM-02 also underwent 1000 nonpeaking LEO cycles prior to the series test. The engineering model testing to date consists of ORU characterization, independent ORU cycling, and series cycling.

A typical battery cell mounting configuration on the ORU baseplate/finned radiant heat exchanger (RHX) is shown in Fig. 1.

**Table 1 Required per ORU orbital power**

| Condition | Time, min Start | Time, min End | Energy, W-h | Power, W |
|---|---|---|---|---|
| *Continuous power requirements* | | | | |
| Constant power charge | 0.0 | 43.9 | —— | 1995[a] |
| Taper charge | 43.9 | 57.0 | —— | —— |
| Total charge | —— | —— | 1677[a] | —— |
| Constant power discharge | 57.0 | 92.0 | 1342 | 2300 |
| *Peaking power requirements* | | | | |
| Constant power charge | 0.0 | 7.5 | —— | —— |
| Constant power charge | 7.5 | 43.9 | —— | 1554[a] |
| Taper charge | 43.9 | 57.0 | —— | 2072[a] |
| Total charge | —— | —— | 1677[a] | —— |
| Constant power discharge | 57.0 | 84.5 | 967 | 2110 |
| Constant power discharge | 84.5 | 92.0 | 375 | 3000 |
| Total discharge | | | 1342 | —— |
| *Contingency power requirements* | | | | |
| Constant power discharge | 0.0 | 92.0 | 997[a] | 650 |

[a]Designates a maximum value.

Presented as Paper 94-3870 at the 29th Intersociety Energy Conversion Engineering Conference, Monterey, CA, Aug. 7–12, 1994; received Sept. 29, 1995; revision received Feb. 14, 1996; accepted for publication March 8, 1996. 

*Technical Specialist, Rocketdyne Division, 6633 Canoga Avenue, P.O. Box 7922.

†Technology Project Development Manager, 21000 Brookpark Road.

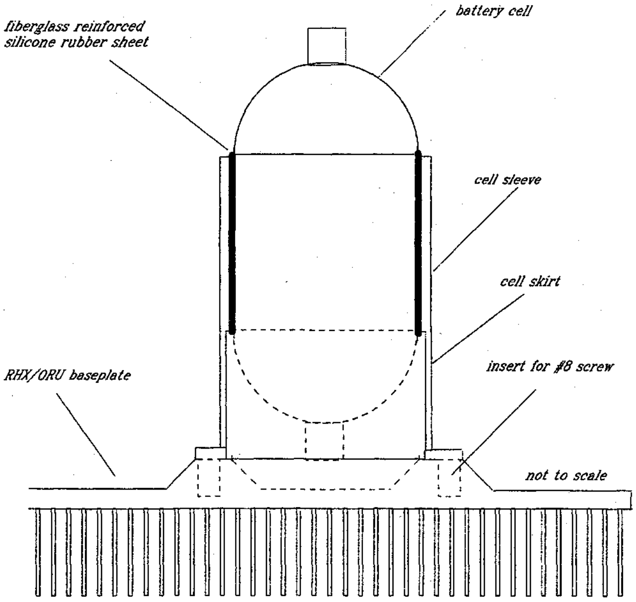


**Fig. 1 Typical Space Station battery cell mounting configuration (for illustration only).**

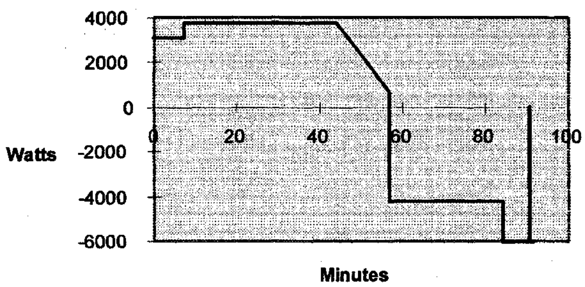


**Fig. 2 Space Station orbital power profile.**

To date, the engineering model battery (two ORUs in series) has completed over 3800 LEO cycles at 35% depth of discharge (DOD) and 5°C (41°F). The following sections will describe the test method and the results of testing to 3000 cycles.

## Test Method

All testing was performed at atmospheric pressure. Hydrogen sensors are installed in the exhaust lines of both chamber compartments to detect possible $H_2$ leakage from cells. Active thermal control is provided by individual radiant finned heat exchangers connected to a recirculating fluid chiller through parallel cooling loops. Closed-cell foam sheet formed into boxes, surrounds the ORUs and thermal interfaces thermally isolating the assemblies from the recirculating nitrogen atmosphere. This was done to minimize convection cooling effects and to cause heat removal to be accomplished primarily through the active cooling system.

All tests were performed using a custom-designed automatic control and data acquisition system. The ORUs were monitored 24 h/day for total ORU and individual cell voltages, cell pressure, and temperatures. ORU power and current, as well as chamber and chiller temperatures were also recorded. Performance characteristics were monitored by plotting end of charge (EOC) and end of discharge (EOD) voltage, pressure, and temperatures to create trend lines. The slope, as well as the spread of the data provides the results described.

These engineering model ORUs, including the enclosures and the radiant finned heat exchangers, are basically the same design as the qualification and flight Space Station ORUs. The ORU instrumentation channels consist of 38 individual cell voltages, a total ORU voltage, four-cell mounted strain gauges, and nine thermistors (six on the cell sleeves and three on the baseplate). Additional temperature sensors were installed for engineering information and will not be present in the flight units.

Upon completion of the individual cycling testing, phase two was initiated. This involved placing the ORUs in series

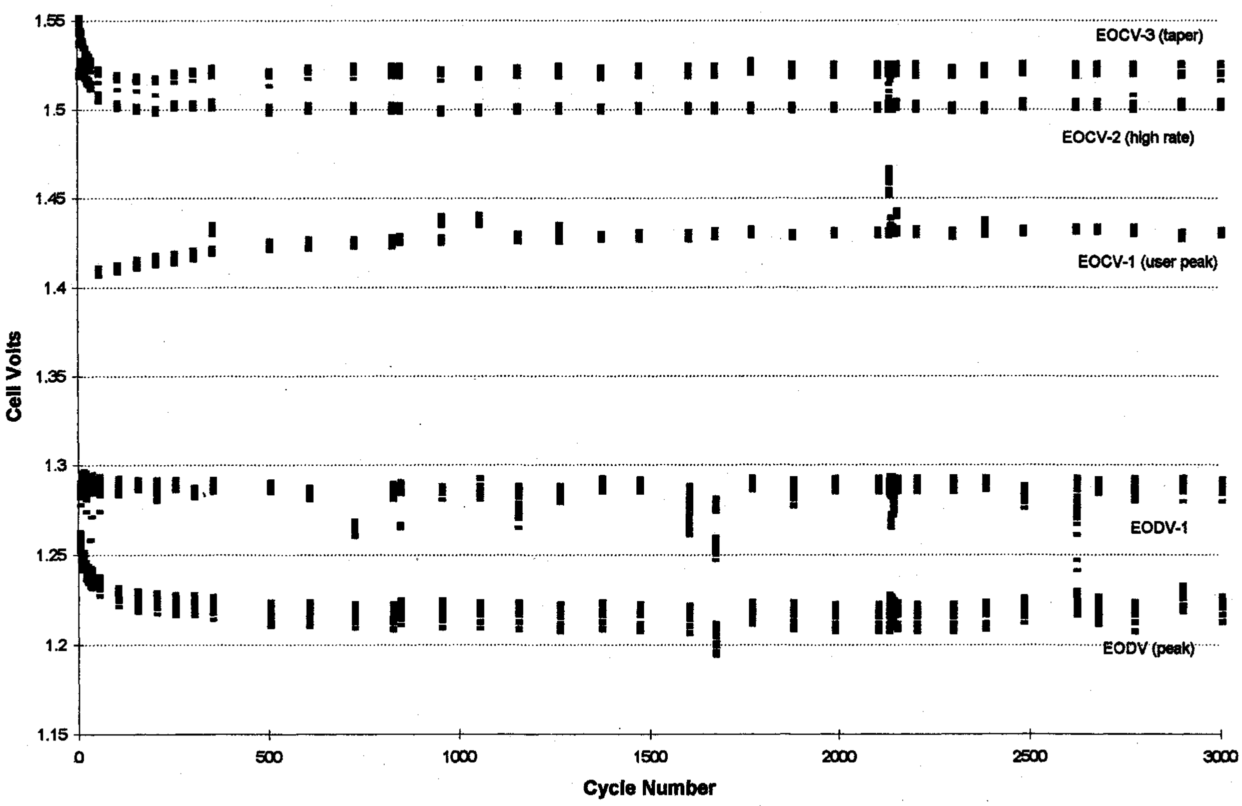


**Fig. 3 EM-01 individual cell voltage trend and spread.**

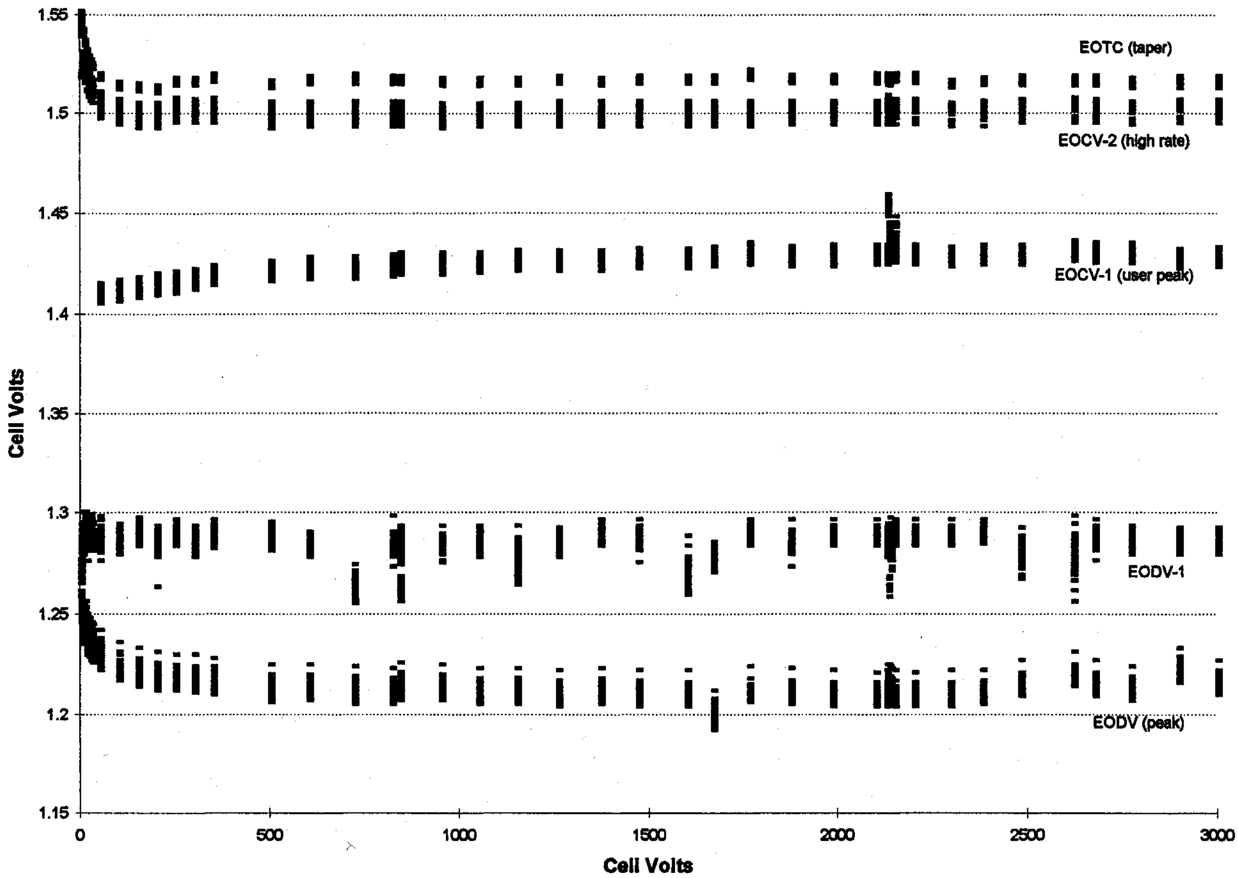


Fig. 4 EM-02 individual cell voltage trend and spread.

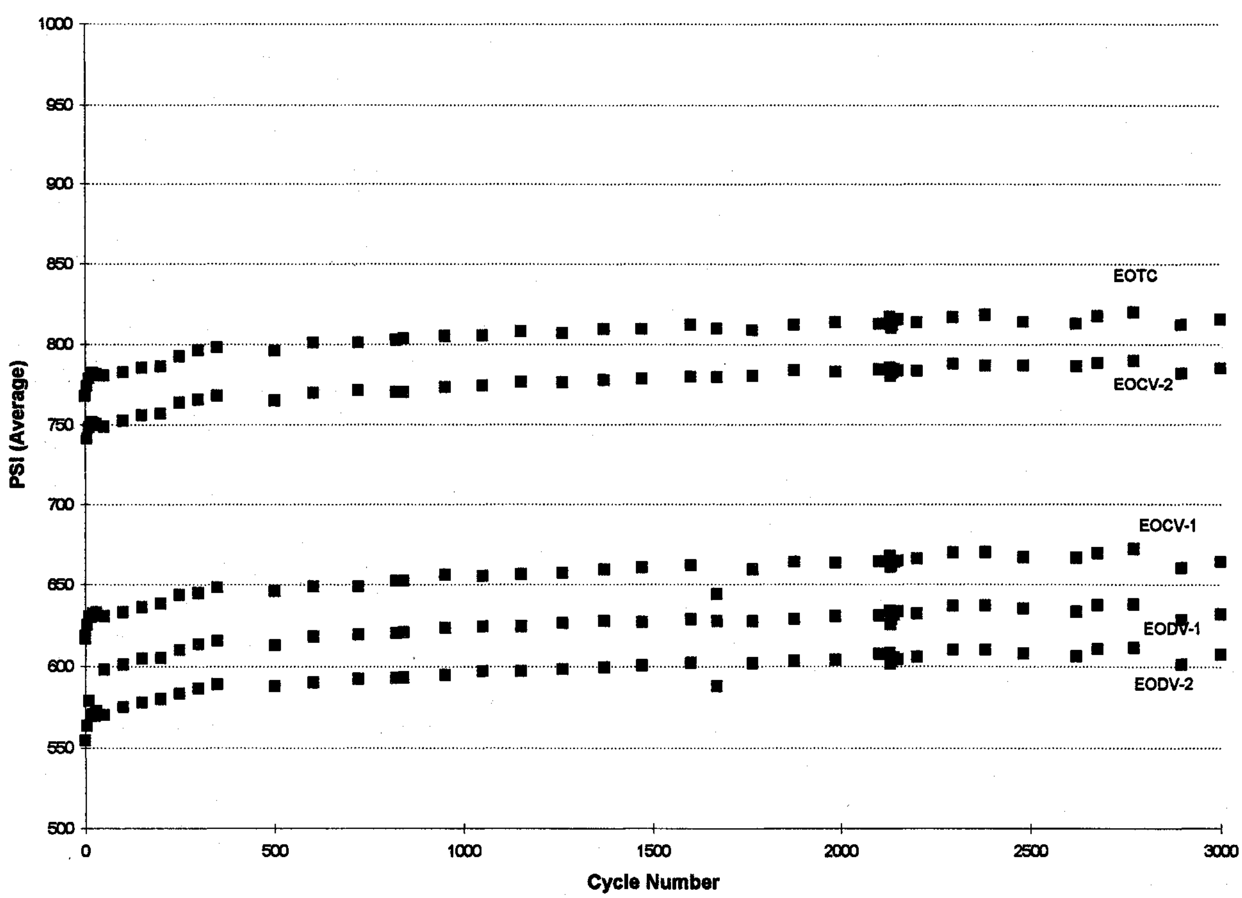


Fig. 5 EM-01 monitored average cell pressure.

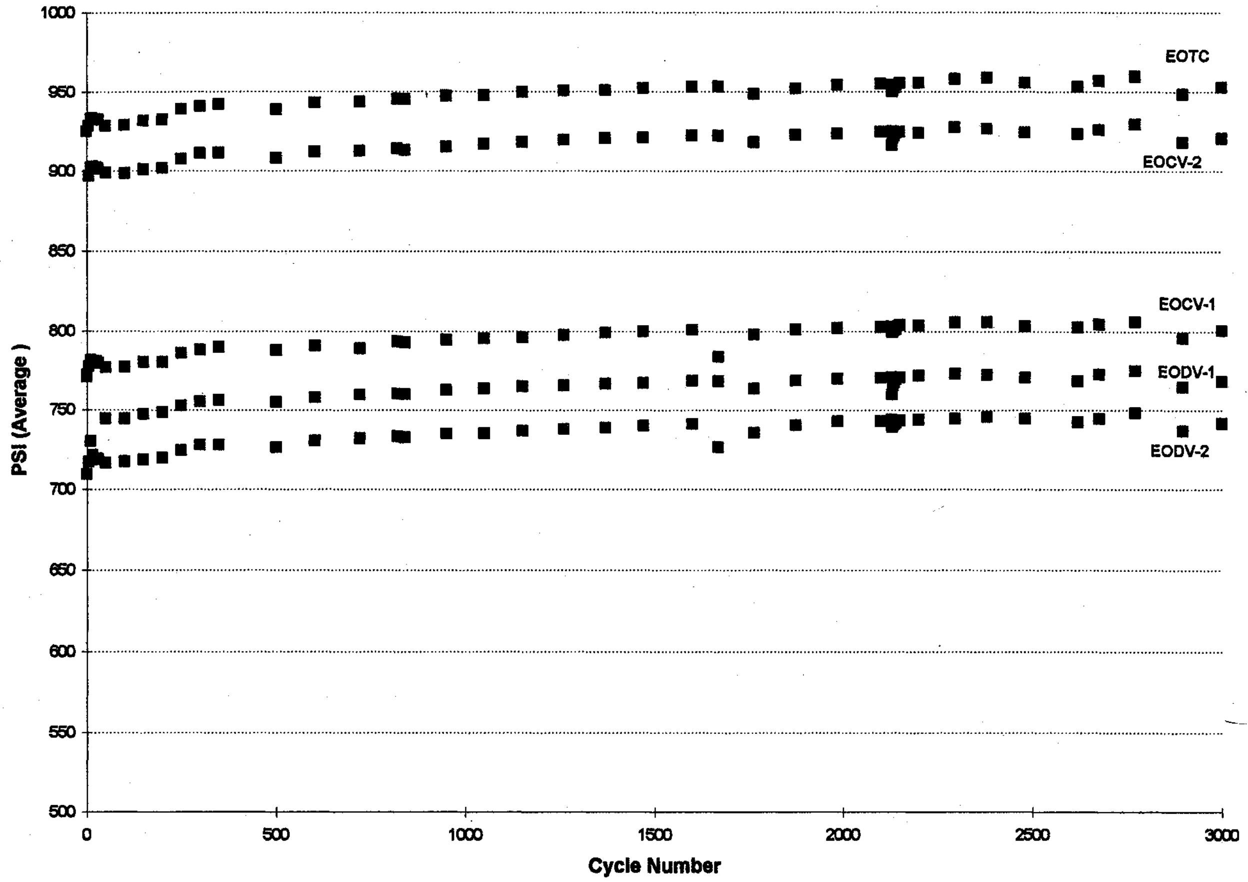


**Fig. 6 EM-02 monitored average cell pressure.**

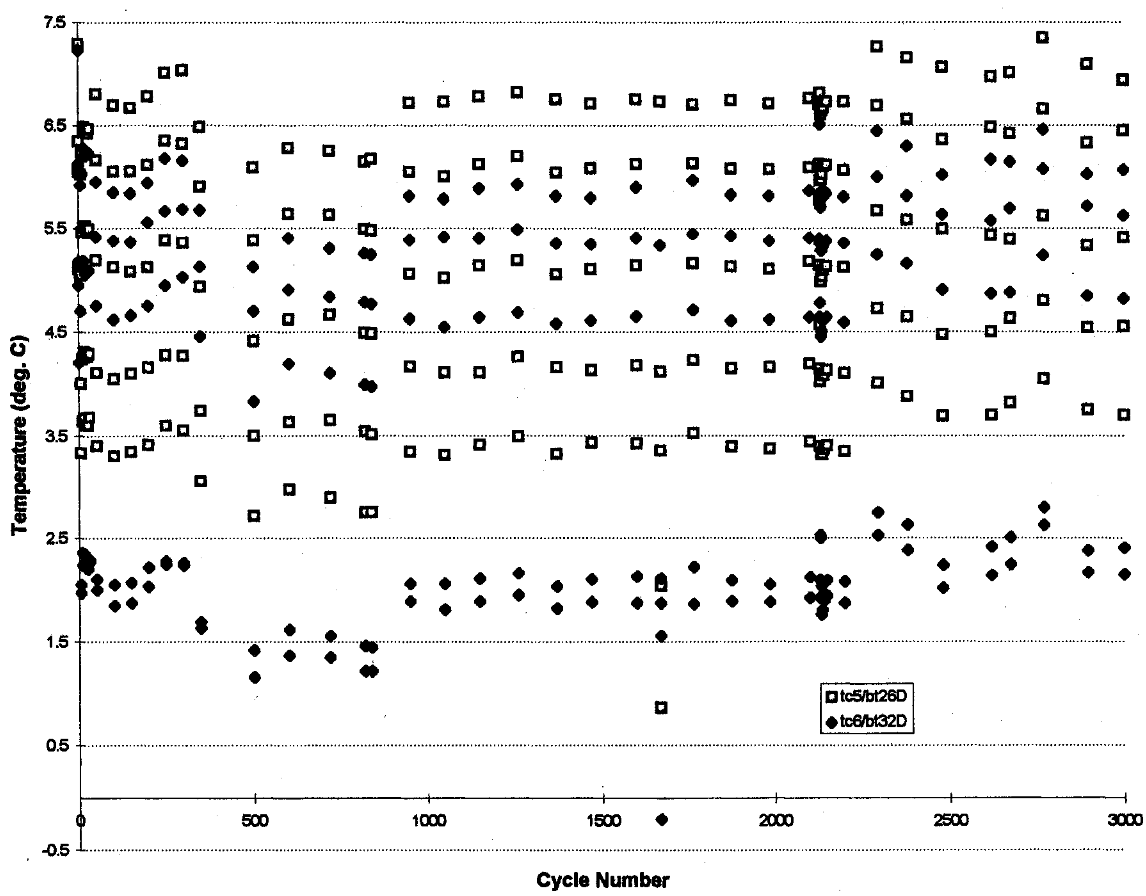


**Fig. 7 EM-01 monitored cell dome temperatures (two cells).**

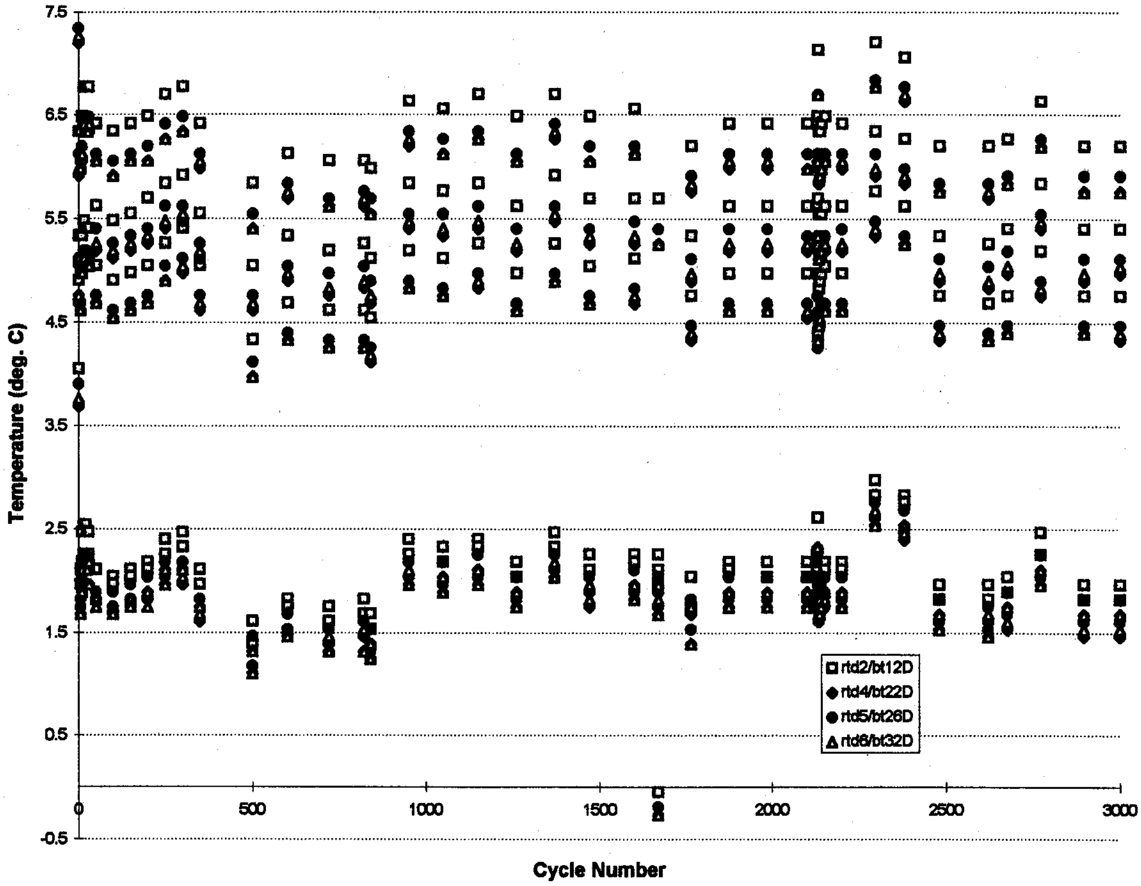


**Fig. 8 EM-02 monitored cell dome temperatures (four cells).**

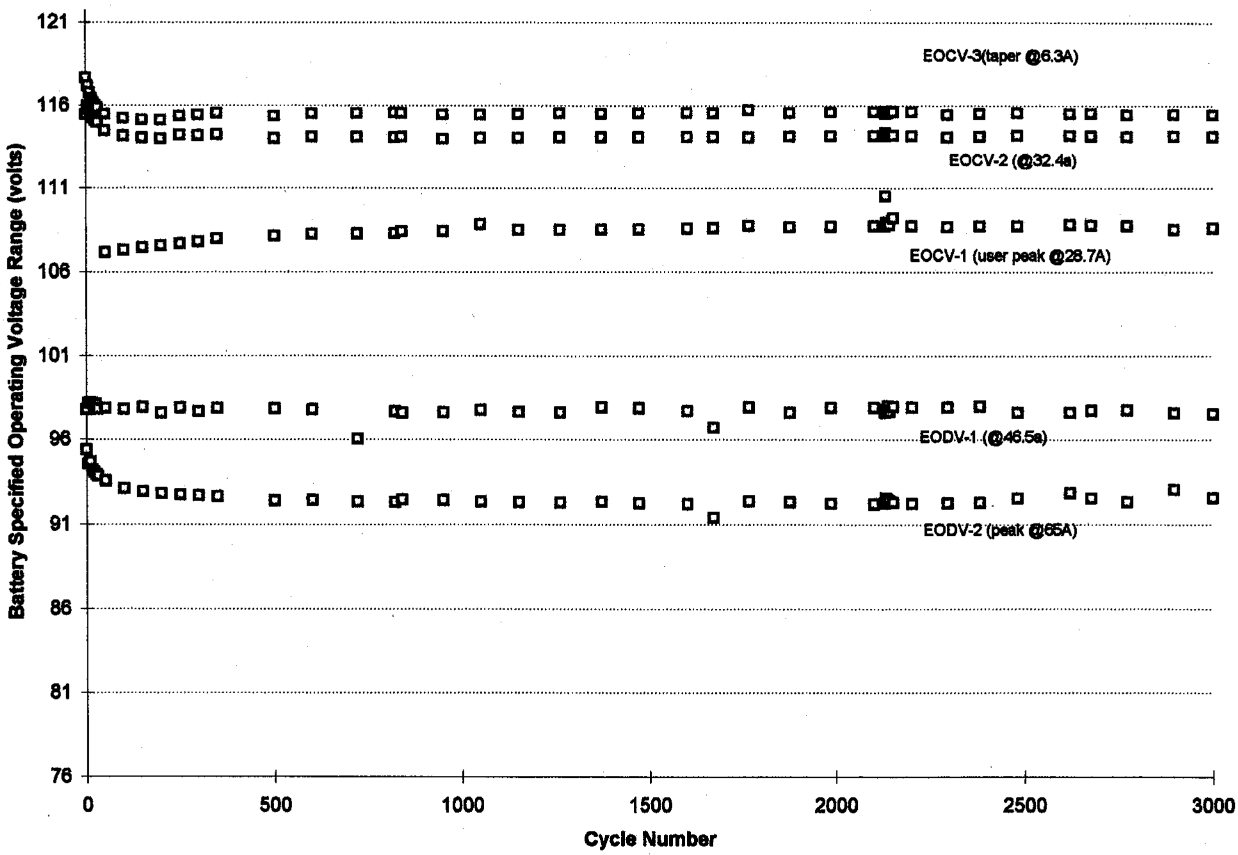


**Fig. 9 Total battery voltage trend plot.**

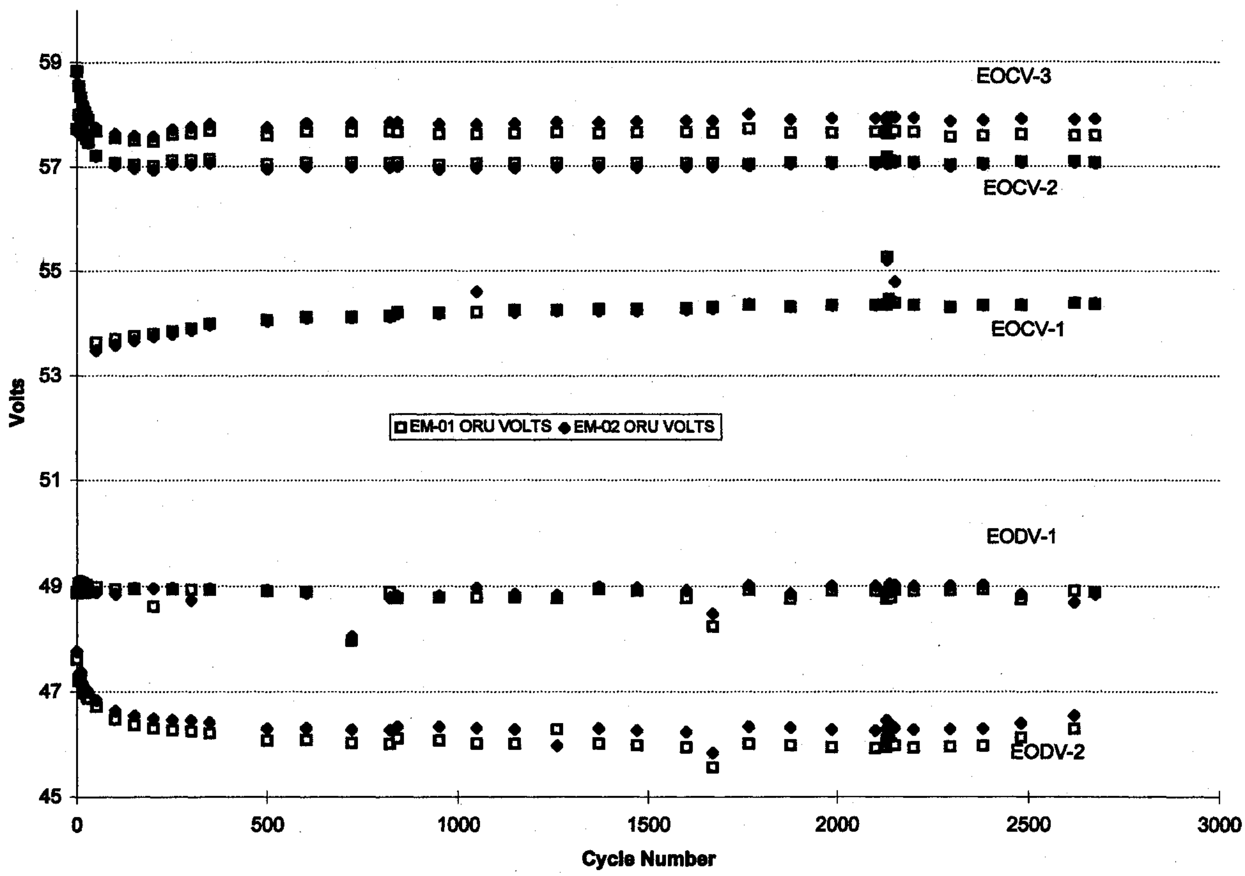


Fig. 10 ORU voltage comparison, trend plot.

**Table 2 Space Station simulated peaking orbit, ≤35% DOD, 1.043 RR**

| Battery ORU orbit power | Time, min |
|---|---|
| Charge, W | |
| 3108 | 7.5 |
| 3746 | 36.4 |
| 3746 > 700 | 13.1 |
| Total | 57.0 |
| Discharge, W | |
| 4220 | 27.5 |
| 6000 | 7.5 |
| Total | 35.0 |

and performing an additional 3000 LEO cycles. These cycles represent the Space Station battery on-orbit duty cycle, including taper charge, which has been optimized to a recharge return ratio (RR) of 1.043, or 104.3% of the ampere-hours removed during discharge. The Space Station power requirements are specified in units of watts and therefore the cycle regime is power based. The 3000 peaking cycles were performed using the maximum discharge power delivery requirement and an optimized recharge regime per Table 2 and Fig. 2. The test was performed while maintaining the cell sleeve temperatures between 0–10°C.

The charge consists of three steps. The first step is at a constant power of 3108 W for 7.5 min, followed by the second step of 3746-W constant power for 36.4 min. The recharge ratio is adjusted if necessary using this step. The final charge step is a power taper, from 3746 to 700 W in 13.1 min. The discharge is a two-step process. The initial discharge is performed at 4220 W for 27.5 min, followed by the peak discharge portion at 6000 W for the final 7.5 min.

Following completion of 3000 series cycles, the ORUs were subjected to two individual orbital rate capacity tests, to determine any degradation in performance. Long duration cycling was planned as a follow-on to the 3000 series cycles. The long-duration testing originally planned was discontinued because of program funding constraints.

## Results

The cell delta voltage within each ORU was less than 0.020 V throughout the test. Divergence or voltage spread is shown in Figs. 3 and 4. Cell pressure stabilized within the first 800 cycles and remained relatively steady throughout the test. The cells generate approximately 7.8 psi (0.53 bar)/A-h and had a total EOC pressure increase of 37 psi (2.52 bar) for EM-01 and 28 psi (1.90 bar) for EM-02 at cycle 3000. EM-02 typically ran 137 psi (9.32 bar) higher than EM-01 (Figs. 5 and 6). Since each ORU was constructed with different cell lots it is not clear whether the pressure difference is real or attributable to strain gauge hardware. The battery ORUs performed nominally and within specification requirements.

The ORUs surpassed the Space Station delta temperature requirements. The as-designed ORU in the simulated configuration maintained good temperature uniformity, less than 1.5°C (2.7°F) across each baseplate. Trend plots of the cell dome temperatures are shown in Figs. 7 and 8. As a battery, the minimum to maximum temperature from cell no. 1 through cell no. 76 was less than 3.0°C (5.4°F).

EM-01 voltages ran slightly higher than EM-02 during both charge and discharge except during the second charge (Fig. 9). A comparison between the two ORUs throughout the 3000 cycles indicates less than a 0.035-V difference (Fig. 9). The ORU voltages stabilized after approximately 300 cycles (Fig. 10). Good charge management and thermal uniformity were apparent. During this phase there were several test interruptions. After several restarts, where the battery received addi-

Table 3 Capacity characterization

| Battery subassembly ORU serial number | @47.4A, A-h | @4.05A, A-h | Total, A-h |
|---|---|---|---|
| Capacity at cycle no. 0 | | | |
| EM-01 | 69.3 | 10.3 | 79.6 |
| EM-02 | 69.4 | 10.0 | 79.4 |
| Capacity at cycle no. 3000 | | | |
| EM-01 | 69.9 | 12.1 | 82.0 |
| EM-02 | 73.3 | 13.1 | 86.4 |
| Post- vs preseries cycling capacities | | | |
| EM-01 | +0.6 | +1.8 | +2.4 |
| EM-02 | +3.9 | +3.1 | +7.0 |

tional recharge to recover capacity lost to self discharge, it was found that cycling could be resumed without special procedures. In a demonstrated case where 14 h of open circuit elapsed, the ORUs recovered and stabilized at their previous (preinterruption) voltages, pressures, and sleeve temperatures after approximately 20 orbits.

The efficiency also surpassed Space Station requirements with watt-hour efficiency at 85% ($W\text{-}h_{out}/W\text{-}h_{in}$) and coulombic efficiency at 96% ($A\text{-}h_{out}/A\text{-}h_{in}$).

Orbital average heat generation increased from 149 to 152 W for EM-01, and 150 to 154 W for EM-02. This is a very slight increase during the test of 2–3%.

Individual ORUs were orbital rate capacity tested before and after the 3000 series cycles. The results are compared in Table 3. Orbital rate capacity testing involves charge and discharge at the rates and profile that will be used in orbit. Both ORUs increased in capacity following the 3000 cycle test. This indicates no performance degradation caused by series operation.

## Summary and Conclusions

The ORU and battery voltage performance was stable at the target recharge return ratio of 1.043. Individual cell voltage data for all 76 cells showed them to be closely matched with little divergence. Cell pressures stabilized. The ORU capacity remained stable, in fact, increased slightly after cycling. Although there were numerous test interruptions, no ORU related anomalies were observed. The two ORUs completed 3000 series LEO cycles with excellent performance. The battery exceeded all Space Station requirements.

## Acknowledgments

The authors wish to acknowledge the contributions and support of Space Systems Loral and the project test engineers and operators, R. Townsend, R. Wolszyn, and D. Spina.

## References

[1]Lowery, J. E., Lanier, J. R., Hall, C. I., and Whitt, T. H., "Ongoing Nickel-Hydrogen Energy Storage Device Testing at George C. Marshall Space Flight Center," *Proceedings of the 25th Intersociety Energy Conversion Engineering Conference* (Reno, NV), Vol. 3, AIAA, Washington, DC, 1990, pp. 28–32.