ELSEVIER

Journal of Power Sources 76 (1998) 210–214

JOURNAL OF POWER SOURCES

# Orbital simulation life tests of nickel hydrogen batteries with additional non-eclipse cycles

P.J. Johnson *, S.W. Donley, D.C. Verrier

*TRW Space and Defense, One Space Park, Redondo Beach, CA 90278, USA*

Received 9 October 1998; accepted 15 October 1998

## Abstract

Nickel–hydrogen battery technology has established itself as the system of choice to provide energy storage on board Earth orbiting satellites. In addition to providing electrical power for the satellite during the periods the satellite's solar arrays are eclipsed by the Earth, applications are evolving (such as ion propulsion) where the battery is required to supplement the power supplied to the spacecraft by the solar panels in order to meet the peak power demands. In this paper, the results of a four-year accelerated life test programme, equivalent to more than 20 years in orbit, are reported. Additional non-eclipse cycles were added to both the eclipse and solstice seasons of each simulated spacecraft year. The results show that the additional discharges do not significantly effect the rates of performance degradation of the batteries. © 1998 Elsevier Science S.A. All rights reserved.

*Keywords:* Orbital simulation; Nickel hydrogen batteries; Non-eclipse cycle

## 1. Introduction

Nickel–hydrogen battery technology has firmly established itself as the system of choice for both geostationary (GEO) and low Earth orbit (LEO) communications and surveillance satellites that require long-life, low mass and highly reliable energy storage systems. Since their development by COMSAT Laboratories in the early 1970s [1,2] nickel–hydrogen cells have undergone several advances [3,4]. The change from hydrogen to nickel precharge (i.e., a deficit amount of hydrogen or an excess capacity of the nickel cathode such that the cell capacity is limited by the amount hydrogen present) for example was found to reduce capacity loss during storage [5]. These changes have been validated by life test, both by the battery manufacturers and their customers. A comprehensive nickel–hydrogen satellite battery life test programme has been in progress at the Naval Surface Warfare Center at Crane, Indiana for more than 10 years, and it is there that many of the nickel–hydrogen design changes have been validated [6].

Concurrent with the evolution of nickel–hydrogen battery technology, there has been a steady increase in satellite payload power requirements, leading to increased battery capacity and a desire to operate batteries to higher depths of discharge. The satellite solar arrays were sized to meet the continuous power requirements during sunlight with the batteries providing reserve power during the eclipse periods. The development of ion-propulsion systems for North–South station keeping [7] offered significant economic benefits by reducing the amount of chemical propellant required for a given mission [8]. However, these benefits would be negated if it were necessary to increase the size of the solar arrays to meet this additional, intermittent power requirement. This additional load will therefore be met by the battery, which will perform a load levelling function during solstice periods by powering the ion propulsion thrusters as required and then being recharged during the remainder of the sunlight period. A 200 mN thruster, for example, typically requires a power input of 5–6 kW. For small satellite applications, the use of sub-kW class ion thrusters may also provide performance benefits [9]. There are other periods when the battery may be required to provide additional power, such as when a solar array is shadowed by the spacecraft's antennas or during a lunar eclipse, for example.

In this work, we have cycled two six-cell nickel–hydrogen batteries using an accelerated orbital profile with the addition of up to sixty supplementary discharges per simu-

---

* Corresponding author. Tel.: +1-310-812-7429; e-mail: philip.johnson@trw.com

0378-7753/98/$19.00 © 1998 Elsevier Science S.A. All rights reserved.
PII: S0378-7753(98)00169-4

Table 1
Cell Characteristics from each life test group

| Parameter | LT1 | LT2 |
|---|---|---|
| Designation | RNH 65-15 | RNH 76-15 |
| Rated capacity, Ah | 65 | 76 |
| Separator type | Asbestos | Zircar |
| Separator layers | 1 | 2 |
| Cathode thickness, mm | 0.762 | 0.762 |
| Number of electrode pairs | 48 | 56 |
| Maximum operating pressure, MPa | 5.0 | 5.0 |
| Precharge | Hydrogen (−) | Nickel (+) |

lated orbital year. Both groups of cells were manufactured by Eagle Picher Industries. The first life test (LT1) was started in March 1992 using six cells of 65 Ah capacity that were spares in a lot of cells designated for flight. A subsequent spacecraft had a higher power requirement and cells of 76 A · h capacity were procured and a second life test (LT2) began in May 1994. The characteristics of the two cell groups are compared in Table 1. The major design changes between the two procurements were the change from single layer asbestos to double layer ZIRCAR™ separators and from hydrogen to nickel precharge. Both these cell designs have been described previously in considerable detail [10]. Note that nickel precharge cells in general operate at lower pressures than hydrogen precharge cells of the same capacity, but in this work, the 76 Ah LT2 cells used the same size pressure vessels as their 65 Ah counterparts, and the maximum operating pressure was estimated to be the same for both cell designs.

The mission simulated is a GEO type orbit having two eclipse periods per year. These eclipse periods may be of a minimum duration of 45 days and a maximum duration of up to 95 days, dependent on the orbit eccentricity. For the purposes of this life test an eclipse season duration of about fifty-nine days each was selected as an average figure. The depth of discharge on the peak eclipse day was estimated to be 55% with the cell packs being discharged at constant power. In addition, during part of the year there may be about 100 additional cycles with a maximum depth of discharge of about 25%. The required mission life for geostationary spacecraft is typically 10 to 15 years.

## 2. Experimental

The six cells in each pack were mounted in sleeves in the same manner as the anticipated flight battery configuration. These sleeves were mounted on an aluminium base plate in a close packed arrangement, with a thin layer of RTV-11 between the sleeves and the base plate. Heaters were mounted around the sleeves and were controlled by a thermistor on the top of the sleeve of cell number 5. The cells were electrically connected in series. The base plate was 12 mm thick and extended 25 mm beyond the cells, around their periphery. Thermal insulation, the size of the base plate, was placed between the base plate and the cold plate. The insulation comprised a sheet of 6 mm thick epoxy fibreglass with approximately 0.25 mm of RTV on each side. Each cell pack was wrapped in thermal insulation so as to minimise heat transfer other than to the cold plate. The entire unit was under a cover that was continuously purged with dry air. The test configuration is shown in Fig. 1. It was established by thermal analysis and test that this cell configuration and thermal insulation would closely simulate the cells' on-orbit thermal environment with the cold plate maintained at 0°C.

The accelerated test regime had 1 year of in orbit battery performance simulated by compressing all the cycles into a period of approximately eighty real days. The discharge profile used in these tests is shown in Fig. 2, which shows the discharge event as a function of accelerated 'days'. The solstices were reduced to seven real days,

**F**

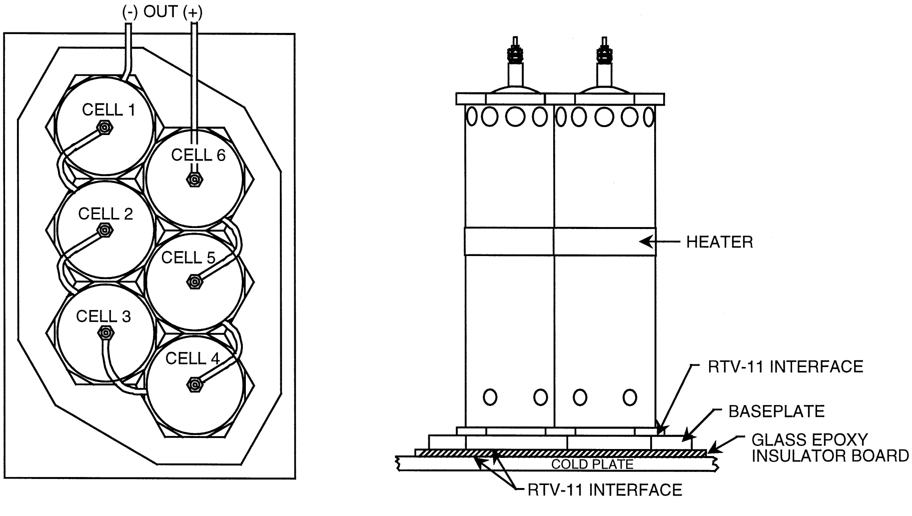

Fig. 1. Test configuration for life tests.

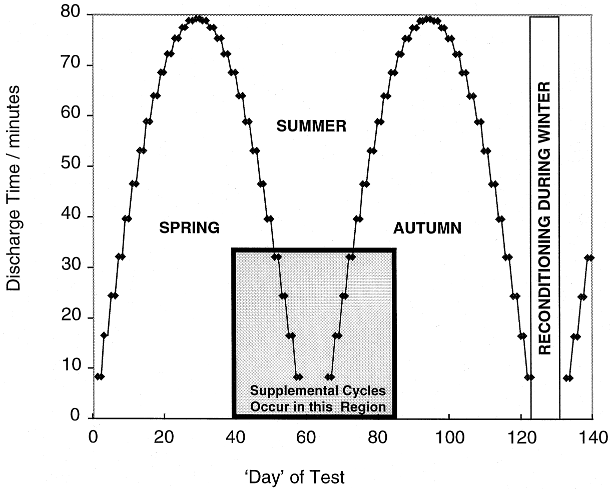

Fig. 2. Accelerated test profile.

with supplemental discharges only occurring in the summer season at a rate of two per day and reconditioning of the cell packs occurred during the winter solstice. Supplemental discharges were performed during the last twenty days of the vernal equinox season and the first twenty days of the autumnal equinox season. Note that as this was an accelerated test the seasons referred to in Fig. 2 do not correspond to the real time of year; they are just a convenient label for each portion of the test. Each cycle is performed as follows: discharge at constant power, 213 W for pack 1 and 249 W for pack 2, for the desired eclipse duration, then recharge at constant current at the $C/10$ rate to restore charge. The latter was achieved by charging to return a capacity equal to that just discharged plus an ampere-hour differential to ensure a full state of charge is reached. This differential, which was 10% of the capacity discharged on the longest eclipse day, was added to the recharge capacity of every cycle in the life test. Following completion of main charge, the cell pack was switched to trickle charge at the $C/100$ rate for a minimum of 4 h. It had been established that the pack temperatures would stabilise at the trickle charge condition within this 4-h period. It should be noted that the reduction of the trickle charge period to 4 h was the only test acceleration applied during the simulated eclipse seasons. A supplemental discharge was performed before the next eclipse if required for that day, with the same recharge criteria. (A 'day' therefore contained an eclipse discharge, a supplemental discharge, or both an eclipse discharge and a supplemental discharge, with recharges taking place immediately after each discharge). The next cycle in the sequence was then started. The sequence of events throughout the simulated year is summarised in Table 2.

Reconditioning was achieved by attaching a 15 Ω resistor across the pack until the pack voltage was below 6.0 V. This required 5 to 6 days. The packs were then charged at $C/10$ for 16 h followed by trickle charge at $C/100$. The duration of trickle charge was at least 24 h before the onset of the next eclipse season.

Table 2
Sequence of events during a simulated spacecraft 'year'

| Day number | Season | Discharge events |
|---|---|---|
| 1 to 39 | Spring | Eclipse only |
| 40 to 59 | Spring | Eclipse followed by supplemental |
| 60 to 66 | Summer | Supplemental, two per day |
| 67 to 106 | Autumn | Supplemental followed by eclipse |
| 107 to 126 | Autumn | Eclipse only |
| 127 to 134 | Winter | Reconditioning |

## 3. Results and discussion

### *3.1. End of discharge voltage and end of charge voltage*

For the mission simulated here, it was a requirement that the flight batteries (which contain 23 cells each) be able to maintain the spacecraft bus at a voltage above 24 V throughout the mission. This corresponds to an average minimum cell voltage of 1.043 V, or, for the six cell packs used in these tests, the voltage minimum is 6.258 V. Fig. 3 shows the load voltage for the test packs at the end of the longest eclipse (day 29 of the 58-day season) as a function of season number, and Fig. 4 shows the pack voltage at the end of the following recharge phase. Several points are worthy of note.

LT2 performance over 20 seasons has been consistently better than LT1, both in terms of end of discharge voltage and of voltage degradation.

After the first few seasons, the end of discharge voltage on day 29 of the eclipse season for LT1 steadily decreases at a rate of ≈ 0.4 mV/cell/season. By contrast, after the first few seasons, the end of discharge voltage on day 29 of the eclipse season for LT2 steadily increases at a rate of ≈ 0.6 mV/cell/season.

The end of charge voltage for LT1 increases at a rate of ≈ 0.4 mV/cell/season, while for LT2 the rate is ≈ 0.2 mV/cell/season.

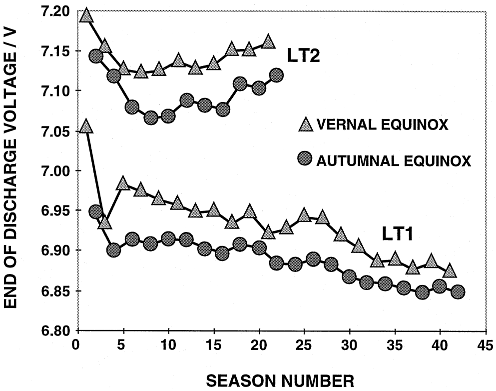

Fig. 3. End of discharge voltage on the longest eclipse days.

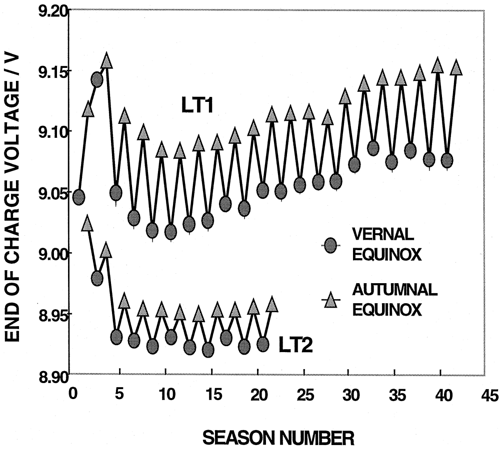

Fig. 4. End of charge voltage on the longest eclipse days.

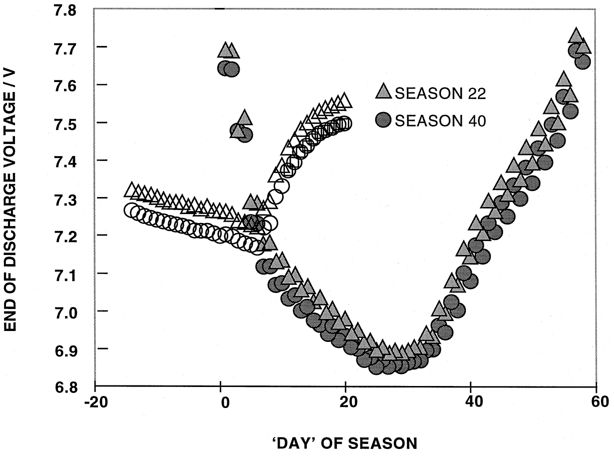

Fig. 6. Life test 1 autumn eclipse seasons.

The end of discharge voltage was always lower for the autumnal seasons than for the spring seasons while the end of charge voltage was always lower for the spring seasons than for the autumnal seasons. This is attributed to the annual reconditioning event. It should be noted, however, that even with the end of discharge voltage decline observed for pack LT1, after 43 seasons, its lowest end of discharge voltage corresponds to 1.14 V/cell.

## 3.2. Eclipse performance

Note: Throughout this paper, when a plot showing both eclipse discharge data and supplemental discharge data is presented, the eclipse data are represented by a full data point symbol whereas the supplemental data are represented by an open data point symbol.

### 3.2.1. Spring eclipses

Fig. 5 compares two spring eclipse seasons (21 and 41) for the LT1 pack. Note that the end of discharge voltages were lower for season 41 than they were during season 21, as expected from the data presented in Fig. 3. Also of interest is the voltage at the end of the supplemental discharges as a function of the day of the season. As all of the supplemental discharges were to the same depth of discharge little end of discharge voltage variation was expected, as indeed was the case during the summer solstice when only supplemental discharges occured. The depth of discharge of the preceding eclipse discharge had a marked effect on the end of discharge voltage of the following supplemental discharge. From Fig. 5, it can be seen that as the end of supplemental discharge pack voltage is higher the greater is the preceding depth of the eclipse discharge.

### 3.2.2. Autumn eclipses

The autumn eclipse seasons show a similar pattern, where the curve, presented in Fig. 6, appears as a mirror image of the curve for the spring season and where the interaction between the supplemental discharges and the eclipse discharges is more pronounced. During the solstice cycling and the initial cycles of the eclipse season, there was a gradual decline in the end of discharge voltages for the supplemental cycles. However, as soon as the eclipse depth of discharge exceeded that for the supplemental discharge, the end of discharge voltages for the supplemen-

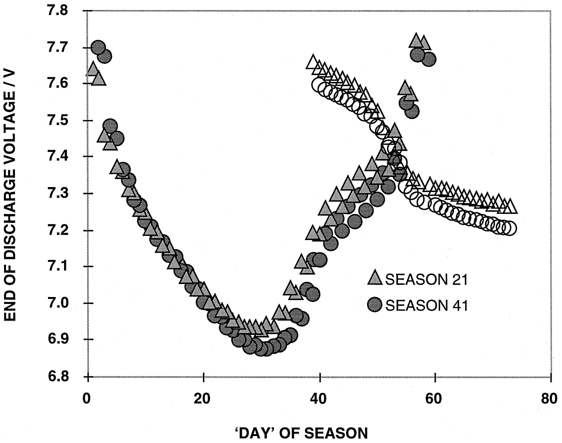

Fig. 5. Life test 1 spring eclipse seasons.

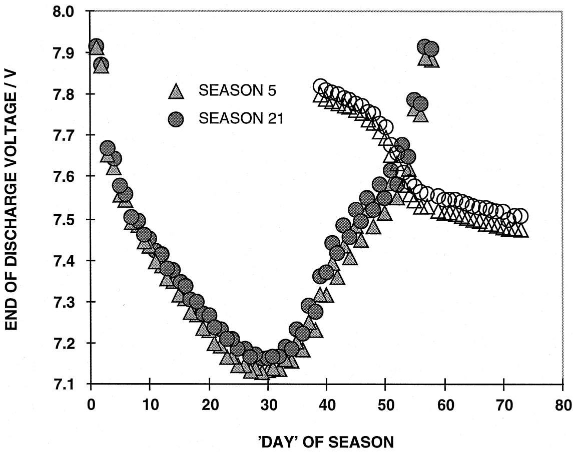

Fig. 7. Life test 2 spring eclipse seasons.

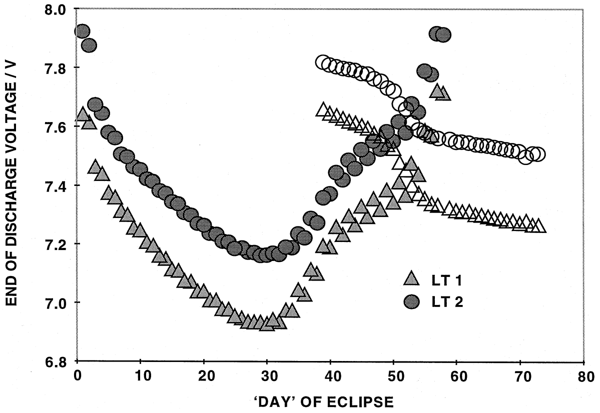

Fig. 8. Comparison of end of discharge voltages for both life test packs, season 21.

tal cycles steadily increased as the depth of the eclipse discharge increased.

### *3.2.3. Life test 2*

A similar pattern was seen on life test 2. Fig. 7 shows the spring end of discharge voltages for seasons 5 and 21. Note that in this test, the end of discharge voltage for the later season was higher than for the early season, in contrast with life test 1. This effect was also seen in Fig. 3, which shows that the end of discharge voltages for LT2 were at a higher level than those for LT1 throughout the test, and the slope of the curve for LT2 was positive, in contrast to that for LT1 which exhibited a negative slope. Whether this is attributable to the different separator materials (asbestos vs. ZIRCAR™) or the type of precharge (hydrogen or nickel) has not been determined in this work.

As was seen in Fig. 3, the end of discharge voltage characteristics of the two cell packs were quite different. Pack 1 showed a lower initial end of discharge voltage that gradually decreased with passing seasons. Pack 2, however, showed a gradual increase in voltage with season. Fig. 8 compares the end of discharge voltages for the two packs after 21 seasons. Both curves are similar, with life test 1 consistently exhibiting a lower end of discharge voltage than pack 2.

## 4. Conclusion

The addition of supplemental discharges has shown no noticeable effect on the lifetime performance of either test pack. Indeed, the deeper of the two discharges that occur on the same day has a beneficial effect on the shallower discharge. This phenomenon has been termed 'shallow discharge reconditioning' [11]. Both test sets have demonstrated their ability to meet a geostationary type of mission profile with considerable margin, with the pack containing ZIRCAR™ separator exhibiting the better voltage profile of the two packs tested. In total, life test 1 performed 2478 eclipse cycles plus 1155 supplemental cycles, and pack 2 achieved 1298 eclipse cycles with 605 supplemental cycles. As it is commonly believed that it is the deep discharge cycles that are the life limiting factor for nickel–hydrogen batteries, these test results demonstrate the robustness of these cells for the class of mission described in this work. Thus, as the testing performed was set to the worst case mission profile, it can be confidently predicted that cells of both designs are capable of meeting all the mission requirements with ease.

## Acknowledgements

This work was partly supported by US Government funding.

## References

[1] J. Dunlop, J. Giner, G. van Ommering, J. Stockel, U.S. Patent 3 867 199, 1975.
[2] J.D. Dunlop, G.M. Rao, T.Y. Yi, NASA Handbook for Nickel–Hydrogen Batteries, NASA Reference Publ. 1314, Sept. 1993.
[3] J.J. Smithrick, P.M. O'Donnell, J. Propulsion and Power 12 (1996) 873.
[4] D.K. Coates, C.L. Fox, J. Propulsion and Power 12 (1996) 879.
[5] H.S. Lim, S.J. Stadnick, J. Power Sources 27 (1989) 69.
[6] S.W. Hall, 27th Annual Report of Cycle Life Test, EDD-96-109, Department of the Navy Crane Division, NSWC Cabd, Indiana, 1996.
[7] D. Roddy, Satellite Communications, 2nd edn., McGraw-Hill, New York, 1996, p. 169.
[8] P.R. Chetty, Satellite Technology, 2nd edn., McGraw-Hill, New York, 1991, p. 286.
[9] M.J. Patterson, S.R. Oleson, Low Power Ion Propulsion for Small Spacecraft, AIAA-97-3060, 1997.
[10] J.D. Dunlop, in: D. Linden (Ed.), Handbook of Batteries, 2nd edn., Chap. 32, McGraw-Hill, New York, 1994.
[11] R.F. Tobias, Proc. 1995 NASA Aerospace Battery Workshop, NASA Conference Publication 3325, 1996, p. 335.